RT-171: Mission Engineering Competencies

Technical Report

Technical Report SERC-2018-TR-106

April 30, 2018

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ACKNOLWEDGEMENTS

EXECUTIVE SUMMARY

Mission engineering is the deliberate planning, analyzing, organizing, and integrating of current and emerging operational and system capabilities to achieve desired warfighting mission effects. (DAG 2017). Though systems acquired within the Department of Defense (DoD) have had a mission context, they have often been acquired individually and not as part of a larger mission. The focus on acquiring systems and systems of systems in a way that supports larger missions is an emerging area.

Supported by a literature review of mission engineering and related areas such as systems of systems and capability engineering, the research team has interviewed 32 individuals who are or have been mission engineers. The views of the mission engineering workforce provide a crucial perspective on the emerging area of mission engineering, in particular, the skillsets which characterize mission engineering competencies. The DoD has defined 'mission engineering', but there is a range of differing views of the definition and scope of mission engineering and its relationship to systems engineering among current practitioners. The differences in views are reflected in this report, including perspectives from US organizations outside the DoD as well as non-US organizations. It should be noted that mission engineering is an emerging discipline and this report reflects the current state of its maturity.

The current core competencies identified by today's mission engineers overlap with competencies which are part of the systems engineering competency base from the Atlas/Helix research, but with added emphasis on key areas, particularly in terms of the critical mission context and operational environment and systems of systems perspectives. (Hutchison et al. 2018) The key competency areas are: Discipline & Domain Foundations, Mission Concept, Systems Engineering Skills, Systems Mindset, Interpersonal Skills, and Technical Leadership.

1. BACKGROUND AND OVERVIEW

This report provides the results of a 16-month study on mission engineering conducted by the Systems Engineering Research Center (SERC). The SERC was tasked by the Office of the Deputy Assistant Secretary of Defense of Systems Engineering (DASD(SE)) with examining the current state of mission engineering practice within the DoD.

Mission engineering in the US DoD is a relatively new endeavor. The key US DoD policy driving the research on mission engineering is the Mission Integration Management (MIM) legislation in the National Defense Authorization Act (NDAA) for Fiscal Year 2017 Section 855 (NDAA, 2017). The recommended mission areas include:

1. Close air support

2. Air defense and offensive and defensive counter-air

3. Interdiction

4. Intelligence, surveillance, and reconnaissance and

5. Any other overlapping mission area of significance, as jointly designated by the Deputy Secretary of Defense and the Vice Chairman of the Joint Chiefs of Staff for purposes of this subsection.

The responsibilities of the MIM activities for a mission area include the following:

1. Developing the technical infrastructure for engineering, analysis, and test, including data, modeling, analytic tools, and simulations;

2. Conducting tests, demonstrations, exercises, and focused experiments for compelling challenges and opportunities;

3. Overseeing the implementation of Section 2446c of title 10 code, United States Code (requirements discussed below);

4. Sponsoring and overseeing research on and development of (including tests and demonstrations) automated tools for composing systems of systems on demand;

5. Developing mission-based inputs for the requirements process, assessment of concepts, prototypes, design options, budgeting and resource allocation, and program and portfolio management; and

6. Coordinating with commanders of the combatant commands on the development of concepts of operation and operational plans.

Section 2446c of title 10 code, United States Code (10 USC 2446c) refers to the requirements relating to availability of major system interfaces and support for modular open system approach and prototyping. The Acquisition Agility Act in the NDAA FY17 Sections 805-809 put the 10 USC 2446c in place. The MIM responsibilities in Section 855 regarding management of interfaces include overseeing the implementation of Section 805. The MIM activities for a

mission area shall extend to the supporting elements for the mission area, such as communications, command and control, electronic warfare, and intelligence. In regards to the US Joint Staff, the key US DoD policy for mission engineering is the Joint Capability Integration and Development Systems (JCIDS) instruction manual in 2015, which mandates mission-based assessments and systems interoperability across US DoD and components.

In 2016, the Acting Deputy Assistant Secretary of Defense for Systems Engineering (DASD(SE)), Ms. Kristen Baldwin started a series of discussions on the topic of mission engineering at the US DoD Systems Engineering (SE) Forum. The intent of these meetings was to begin a discussion between the offices in the Office of the Secretary of Defense (OSD), the Joint Staff, and the organizations performing mission engineering (Gold, 2016). The purpose of these roundtable meetings was to identify policy, organizations, methods, tools, challenges and opportunities for mission engineering enterprise improvements. The series of discussions concluded in an enterprise-level discussion to synthesize mutual approaches, challenges, and potential recommendations for the acquisition committee.

The roundtables were conducted by the DASD(SE) with the following organizations: Army, Navy, Air Force, Missile Defense Agency (MDA), and the Joint Staff. The outcomes were as follows:

- Understanding of current practices: processes, techniques, tools, measures, and the role of modeling & simulation and test & evaluation.

- Identification of actions in policy, resources, and research to affect improvements to current practices; common, persistent challenges, gaps, or obstacles requiring attention; and the initial sense of how DoD sees working with industry.

- Development of a briefing package for DoD component leadership and USD (AT&L), the latter effective in 2018 to be USD(R&E) and USD(A&S).

The Army mission engineering focus, briefed at the roundtable in 2016, was on integrating updated network systems into capability sets for deployment. Beginning in 2017, the Army has stood up initiatives under the aegis of the Futures Command with cross-functional teams (CFTs) addressing the following systems of systems: 1) long-range precision fires; 2) next generation combat vehicles; 3) future vertical lift; 4) air and missile defense; 5) soldier lethality; 6) synthetic training environment; 7) network, command, control, communications and intelligence; and 8) precision, navigation, and timing.

The Navy focus in 2016 was, and remains, integration and interoperability (I&I). This is a Navy-wide initiative for analysis of naval missions to understand how well current systems meet Navy mission needs, and to identify gaps. The Navy seeks to understand integration/interoperability issues between systems and identify where investments are needed to improve mission performance. I&I considers both material and non-material (operational) solutions using Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, Facilities (DOTMLPF). The Navy is in conformance with the Joint Capabilities Integration and

Development System (JCIDS) and Department of Defense Instruction (DoDI) 5000.02 for systems requirements and acquisition. The I&I approach is to use naval mission threads from a system of systems (SoS) mission-level perspective, for the purpose of identifying and prioritizing changes and upgrades in the systems supporting the missions.

Throughout this report, systems of systems are mentioned. A single system of systems is abbreviated SoS, usually when referencing a specific system of systems. If multiple systems of systems or if the general concept of systems of systems are referenced, this will be noted as SoS's.

The Air Force focus is to identify mission sets aligned with the Joint Simulation Environment for the F-35 aircraft. The Air Force is developing a fifth generation modeling and simulation enterprise. There are five core missions and 42 sub-mission sets; the intent is to perform mission thread analysis and assessment across the mission sets to assess key systems and risks. The Air Force also adheres to JCIDS and DoDI 5000.02 for requirements and acquisition, using various analytical techniques in their engineering analysis.

The MDA has a systems engineering office with end-to-end responsibility for the Ballistic Missile Defense System (BMDS) with elements that are systems in their own right managed by both MDA and the services. MDA is exempted from JCIDS and DoDI 5000.02, allowing them to focus their engineering on the set of systems supporting the end-to-end mission; this allows MDA to make trades across systems to meet mission needs from the initial definition associated with each new increment. Hence there is a strong emphasis and substantial investment in modeling and simulation.

The Joint Staff has developed generic mission threads to perform mission analysis. The focus is on joint mission integration using joint mission threads as the foundation for 1) improved interoperability in key areas such as close air support and joint fires, and 2) integration of forces for operations including interoperability assurance and validation of coalition forces. The mission analysis incorporates adversary capability interactions performed manually in house or leveraging other organizations' modeling and simulation capabilities.

In association with the government roundtables, industry formed a task force to assess current industry activities and viewpoints on mission analysis and mission engineering. Supporting organizations for this survey and assessment, led by the National Defense Industrial Association (NDIA) Systems Engineering Division (SED) and the International Council on Systems Engineering (INCOSE), included Military Operational Research Society (MORS), Institute of Electrical and Electronics Engineers (IEEE), Aerospace Industries Association (AIA), and American Institute of Aeronautics and Astronautics (AIAA). The conclusions of the industry survey and assessment is that industry finds value in mission engineering and mission analysis. Industry has a large number of practitioners who use a variety of approaches and tools. Industry respondents desire to work more collaboratively with DoD to refine and understand the definition of mission engineering and address common challenges including sharing best practices, tools, and models; find a means to provide access to relevant data; share resources for skill development; and recommend the establishment of a joint action plan to move forward.

Based on the literature review, several examples of mission engineering work within the US DoD, other government agencies, the US, and capabilities engineering by other nations are highlighted in Table 1, below.

Table 1: Sample Mission Areas for Mission Engineering Work within the US DoD

Current Status	Mission(s)
Currently Addressed	• Ballistic Missile Defense (MDA) • Nuclear Command and Control/National Leader Command and Control (NLCC) • Digitally Aided Close Air Support (DACAS) • Air/Cruise Missile Defense (Navy AEGIS and Army) • Integrated Air Missile Defense (IAMD)
Cross Services Examples	• Tactical SATCOM • CHEM BIO • Environmental Monitoring (Weather) • Spectrum Operations • Assured Position, Navigation, and Timing (PNT) • Cyber Situational Awareness
Needed Mission Engineering Approaches	• Air Superiority in Contested Environments • Wide Area Surveillance and Targeting

In Table 1, "Needed Mission Engineering Approaches" are engineering approaches that are not officially designated as mission engineering, but which many share characterstics with the missions identified for this research (addresses a complex problem requiring a system of systems solution that crosses organizational boundaries).

1.1 PURPOSE OF THE RESEARCH

The purpose of this initiative is to develop a model of the key competencies required for the DoD acquisition workforce to support mission engineering. The competency model will include skills and experiences necessary to perform the following mission engineering activities across complex systems and SoS's including, but not limited to: mission analysis and synthesis, trade-off analyses, technology management, resource management, architecture development and modeling, mission modeling, addressing supporting capabilities (e.g., communications) and overarching mission functions, synchronization of testing and individual system implementation (based on the Department's established 'Systems of Systems Wave Model' and the current 'Systems Engineering Guide for Systems of Systems') as well as reflect industry approaches and best practices. This initiative has active interest among and commitment of support from the Army, Navy, Air Force, MDA, and Defense Advanced Research Projects Agency (DARPA), each of whom have been performing various forms of the above activities in support of their agency-specific mission needs. The US DoD defines mission engineering as the development and deployment of a military capability by applying a mission context to SoS and to complex systems within the Department. Based on the findings of the research, the RT-171 team recommends a broader view:

> ***Mission Engineering combines the structure of systems engineering and the tactical insights of operational planning to a system of systems to deliver a specific capability.***

Mission engineering differs from systems engineering because it necessarily includes a system of systems context: the individual systems that comprise the military capability (e.g. ships or aircraft) are inherently flexible, functionally overlapping, multi-mission platforms supported by a complex backbone of information communication networks. The composition of assets performing missions are dynamic, both spatially and temporally (Garrett et al 2011 and Moreland and Thompson 2017). This context is unlike traditional systems engineering where there is little to no function overlap or flexibility because individual functions are mapped to only one element in the system. SoS has arisen in response to increasingly complex systems being developed by the Department where the capabilities of the multiple linked systems are greater than the sum of the capabilities of the constituent parts. The mission context is a key element to assisting developers and managers to determine which systems have to be involved, what functions they have to perform, and how operators/users will make use of these systems. With the emergence of a mission-focus to SoS efforts over the last five to six years, the engineering community is now able to successfully assess and determine which systems are relevant to a capability and how to modify those systems to support critical mission areas such as air defense and offensive and defensive counter-air; and intelligence, surveillance, and reconnaissance.

1.2 RESEARCH METHOD

The research is based on a mixed-methods approach, utilizing grounded theory to extract meaning from data collected in interviews as well as a traditional literature review. Based on recommendations from members of the Officer of the Secretary of Defense and identified additional interviewees through literature review and recommendation from study participants. The team interviewed 32 individuals who are currently or were recently practicing mission engineers. These individuals came predominantly from the US DoD, though non-DoD US government, US commercial, and non-US government entities were also included. (See Figure 1) The interview questions can be found in Appendix C. The traditional literature review focused on people, processes, methods, and tools used to perform, or propose, mission engineering. The literature review findings are used to corroborate the responses elicited from the interviews.

The team performed qualitative analysis on the interview data, primarily coding for like groups and then developing additional structure based on the content of data, allowing the themes to emerge rather than starting with an expected framework (grounded theory). The results of these qualitative analyses are presented throughout this report. Data groupings included:

- Definition of mission engineering

- Relationship between mission engineering and systems engineering

- Current practices in mission engineering

- Current challenges in mission engineering

- Critical skills for mission engineering

- Expected future challenges for mission engineering

Percentage of Participants by Organization Type (N=32)
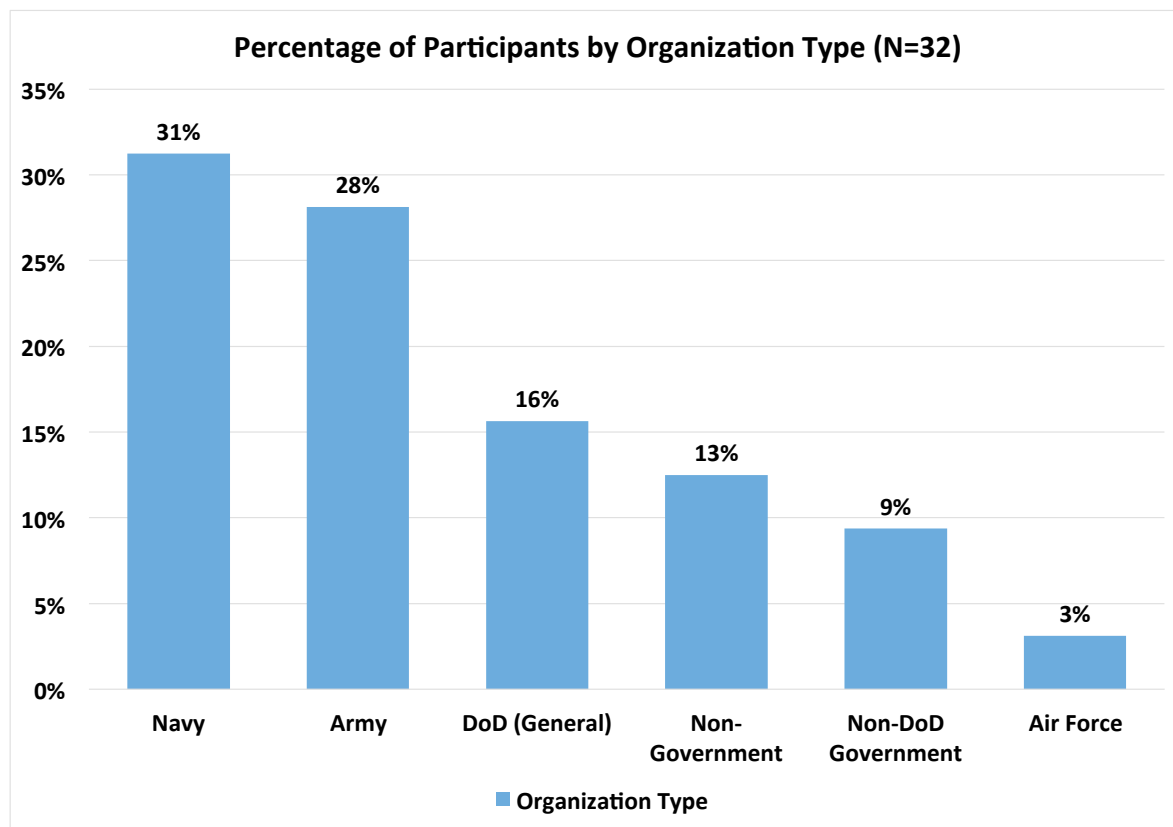
Figure 1. Percentage of participants by organization type.

Another common theme in the data was the importance of systems of systems engineering for mission engineering; however, this is detailed at the next level of analyses below the above groupings. In addition, the team analyzed over 50 sources for their literature review, covering topics such as mission engineering, system of systems engineering, capability engineering, and force design. The results of the literature review are highlighted in Appendix D as well as integrated into the discussions of research findings as appropriate.

1.3 REPORT STRUCTURE

The body of this report is divided into three additional sections:

- **Section 2: Mission Engineering Context** – Based primarily on the interview responses, this section provides an overview of how mission engineering is conducted within the DoD and also reflects lessons learned from other US government agencies and industrial organizations. In addition, this section provides an overview of existing academic programs focused on mission engineering.

- **Section 3: Mission Engineering Competency Framework** – based on all the data collected to date, including the literature review (Appendix D) and the data collected (Appendix E). This section presents a competency framework tailored specifically to mission engineering.

- **Section 4: Future Directions for Mission Engineering** – based on the interview data collected, this section provides perspectives on how mission engineering is expected to evolve.

The body of this report is intended to be concise and streamlined. However, the appendices provide supporting information about how the conclusions in the body of the report were created:

- **Appendix A: Publication List** – This appendix provides a list of publications by the RT-171 team related to this research for additional information.

- **Appendix B: References** – This appendix provides a list of all materials referenced and reviewed as part of the research project.

- **Appendix C: Methodology** – This appendix provides the detailed methodology used by the RT-171 team to conduct the research.

- **Appendix D: Literature Review** – This appendix provides an overview of the critical literature reviewed as part of the research project.

- **Appendix E: Interview Data Analysis** – This appendix provides results of the detailed qualitative analysis conducted by the RT-171 team on the interview data collected throughout the project.

- **Appendix F: Existing Academic Programs in Mission Engineering** – This appendix provides a listing of all programs that have mission engineering related curricula identified by the RT-171 team.

- **Appendix G: Mission Engineering Program at Old Dominion University** – This appendix provides an overview of the only mission engineering degree program identified by the RT-171 team.

- **Appendix H: (ISO/IEC/IEEE) 15288 guidelines –** This appendix provides guidance on the 'Systems and software engineering – system lifecycle processes' standard published jointly by the International Standards Organization (ISO), the International Electrotechnical Commission (IEC), and the Institute of Electrical and Electronics Engineers (IEEE).

2: Mission Engineering Context

This section provides an overview of the state of mission engineering from the perspective of the study participant at the time of publication, with additional information from the literature review.

2.1 What is a Mission?

There are many definitions for the word 'mission', from the colloquial – e.g. 'an important assignment' – to those specific to a given context such as defense, homeland security, or space exploration. The definition of 'mission' for the purposes of this report is:

> The task, together with the purpose, that clearly indicates the action to be taken and the reason therefore. (DoD 2016)

The US Navy approach to mission engineering charges the naval systems commands (SYSCOMs) "to place an increased emphasis on assessing the I&I (integration and interoperability)" of warfare systems to support current and future readiness for critical mission threads. The assessment of naval technologies, systems and/or capabilities requires a system-of-systems (SoS) approach to analyze the impact of making these naval investments across the diverse domains of surface, undersea, air, land, and networks as well as maritime coalition force integration. These assessments are executed following a systematic, quantifiable, and iterative approach referred to as Mission Engineering, which combines the structure of systems engineering and the tactical insights of operational planning. The findings are captured in 'effects/kill chains' to clearly identify operational needs based on the way we plan to fight through mission threads captured in our Combatant Command's Operational Plans (OPLANs) and Contingency Plans (CONPLANs). Mission Engineering emphasizes capability-based assessments to produce integrated war fighting capabilities that can be translated into specific programmatic guidance for strategic programs." (Moreland 2015).

The MDA approach "revolves around the concept of a mission context which manages uncertainties, dynamics and stochastic behaviors of SoS's. It has been posited that complex SoS's are driven not by the performance and behaviors of the constituent components, rather they are driven by the complex integration and interoperability, the interstitials, of the components to achieve Mission-level goals … mission threads are the description of the end-to-end set of activities and component systems employed to accomplish specific subsets of the mission goals and objectives." (Deiotte and Garrett 2013).

A generic 'kill chain' mission thread is expressed as an event-based sequence of operations on a time line: detect, track, engage, assess, and (potentially) re-engage (Garrett, Anderson, Baron, and Moreland 2011). The geolocation of the different generic operations can be on the same or

distributed platforms interworked together; these generic operations, are called 'functions' or 'activities' in systems engineering speak. The allocations of these functions or activities to physical assets can dynamically change over the course of a mission thread. The engineering design of systems, or systems of systems, integrates the set of (dynamically changing) mission threads into a whole using executable modeling methods rooted in graph theory that can be assessed in terms of structural integrity, behavior, performance at scale, and resilience (Buede and Miller 2016). When modeled and integrated in this manner, an individual 'effects/kill chain' mission thread is just one instantiation through a more complicated or complex networked web of capabilities.

Table 2 provides an overview of several examples of missions reviewed by the RT-171 team. Each of these missions is elaborated in Section 2.1.1 – 2.1.4, below.

Table 2: Mission Engineering Examples by other Government Agencies

Organization Name	Type	Mission(s)
US DoD	Enterprise	Intelligence, Surveillance, Reconnaissance (ISR)
	Joint, Multi-Domain	US Pacific Command (PACOM) Joint Operations
	Missile Defense	Ballistic Missile Defense and Theater Missile Defense
	Service-Specific	Navy Ballistic Missile Defense and Anti-Air Warfare
	Service-Specific	Navy All Domain Offensive Surface Warfare Capability and Naval Integrated Fire Control-Counter Air (NIFC-CA)
	Service-Specific	Army Counter Russian Hybrid Warfare
	Service-Specific	Army Brigade Combat Team (BCT) Air and Missile Defense
Federal Aviation Agency (FAA)	National	National Airspace System (NAS)
NASA	Interplanetary Travel	Journey to Mars
US Government (cross-department initiative)	Infrastructure	Critical Infrastructure Protection and Recovery
Australian Ministry of Defense (MOD)	Defense	Australian Land-Force Capability Integration
UK Ministry of Defence	Defense	Generic Vehicle Architecture (GVA)

2.1.1 US DEPARTMENT OF DEFENSE (DoD) MISSION EXAMPLES

The following are several examples of DoD Missions that have been analyzed in this research.

Intelligence Surveillance Reconnaissance (ISR)

ISR providers – service-specific assets that provide intelligence, surveillance, and reconnaissance as well as national means provided by the intelligence community – view themselves as enterprises. The legacy structure of these enterprises is based on a functional design where individual systems are 'owned' by the functional organizations. Capability directorates are overlaid on the functional organization; the capabilities owners think in terms of mission threads to produce ISR products. This results in a natural tension between the owners of the mission threads and the owners of the program systems. A services oriented architecture (SOA) is the common approach to integrate the functional systems to execute the mission threads. The individual systems are viewed as Lego™ blocks to provide a reusable architecture for executing different mission threads.

A draft definition of the problem reflective of the complexity of ISR is as follows. In today's context of a complex, richly interconnected world, enterprises traditionally organized along functional lines face cultural, organizational and technological challenges transforming to capabilities-based enterprises operating at Internet speeds. Their functional models evolve to identifiable organizations within the enterprise, each seeking to optimize their part of a systems of systems. The end result of the enterprise as viewed from the outside is dysfunctional at worst and inefficient at best. Capabilities-based enterprises face their own challenges in terms of creating and sustaining rapid but inefficient custom mission threads versus efficient platform-based mission threads with reusable components. Transformation from the legacy functional enterprise to the capabilities enterprise is hindered by cultural and institutional inertia reinforced with aging installed technology bases. Culture, institutional inertia, incentives, and enabling technologies must all be transformed. The successes of these transformations are limited, but there are success models.

US Pacific Command (PACOM) Joint Operations

PACOM and its service components are proactively working counter anti-access/aerial denial (A2/AD) and joint fires using a fictional joint operations vignette where a hostile power with substantial military capabilities seizes control of an island in the Indo-Asia Pacific region with which the US has treaty obligations requiring military intervention. The island is decisive terrain[1] influencing aerial and maritime navigation or access to a strategic port. The mission is to secure the island and restore unhindered navigation. The mission sequencing is as follows: 1) cyber and space capabilities to temporarily blind and disrupt the hostile power's command and control systems; 2) special operations forces infiltrate the island and template[2] the opponent;

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[1] A geographic place … that, when acted upon, allows commanders to gain a marked advantage over an enemy or contribute materially to achieving success. (DoD 2018)

[2] "Template" is used by the DoD in the context of characterizing/patterning the capabilities, doctrine, etc. of opponents.

3) Marine amphibious forces secure the island including beachhead, airfield, and other major structures; 4) Army engineers follow-on to repair the airfield and construct hardened defensive positions; 5) a reinforced Army Stryker battalion is air landed to replace the Marines and is augmented with 155mm howitzers, HIMARS (rockets) equipped with anti-ship cruise missile pods, and air and missile defense assets to defend the island for an extended period. These forces are protected by Air Force manned and unmanned systems, Navy ships, and underwater drones.

Ballistic Missile Defense and Theater Missile Defense
MDA has end-to-end responsibility for both the ballistic missile defense system (BMDS) and theater missile defense. The BMDS is to defend the US homeland and US regional friends and allies against limited ballistic missile attacks. The BMDS is designed to combine the capabilities of the ground-based midcourse defense (GMD) system with a network of ground-, sea-, and space-based sensors to provide an integrated, layered defense. GMD defends against threats by launching ground-based interceptors that release kill vehicles to find and destroy the threat.

The mission engineering approach for both ballistic missile defense and missile defense defines mission threads as kill chains instantiated as dynamic spatial and temporal graphs combined with agent-based models to analyze performance at scale. A critical element in mission engineering in this domain is managing the interstitials, that is, the interfaces, interoperability, and integration between constituent systems in the system of systems.

Navy Ballistic Missile Defense and Anti-Air Warfare
Navy Aegis combat systems on cruiser and destroyer platforms provide BMDS, theater missile defense, and anti-air capabilities, the latter against both manned and unmanned threat systems. The mission engineering approach for missile defense and anti-air warfare defines mission threads as kill chains instantiated as dynamic spatial and temporal graphs combined with agent-based models to analyze performance at scale. A critical element in mission engineering in this domain is managing the interstitials, that is, the interfaces, interoperability, and integration between constituent systems in the system of systems. There is close synergy in the MDA and Navy approaches to mission engineering.

Navy All Domain Offensive Surface Warfare Capability and Naval Integrated Fire Control-Counter Air (NIFC-CA)
The offensive anti-surface capability ties targeting information from satellites, aircraft, ships, submarines, and the weapons themselves in a 'tactical cloud' to form a kill web. The concept is similar to the carrier strike group NIFC-CA in which aircraft and ships in the strike group share their targeting information on aircraft and cruise missile threats via high-capacity data links to other ships and aircraft that might be out of sensor range, but not out of weapons range of a target. Again, the concepts leverage the kill chain approach from the Aegis program.

Army Counter Russian Hybrid Warfare
Russia has demonstrated sophisticated hybrid warfare approaches in the Ukraine that blend and integrate disinformation campaigns, cyber warfare, insurgency, surveillance drones,

massive artillery/rocket strikes on opposing force assembly areas, and protected by a dense air defense system providing anti-access/aerial denial (A2/AD). The Army is performing mission analysis and engineering to close the gap in capabilities.

Army Brigade Combat Team (BCT) Air and Missile Defense
The Army BCT Air and Missile Defense initiative is to close the gap in BCT air defense against manned aircraft, UAS, cruise missiles, rockets, artillery, and mortars. The Army is employing the joint counter-air framework using attack operations to find, fix, and defeat UAS ground stations in conjunction with indirect fires. Passive air defense measures include cover, camouflage, concealment, and deception to reduce aerial observation. Key assets are hardened, formations dispersed, and redundancy is established for key nodes to reduce the effects of attack. Passive measures also include providing early warning to units. Active defense measures include allocation of assets for non-dedicated air defense, and dedicated air defense artillery.

2.1.2 US Government Agency Mission Examples (Non-DoD)

The following are several examples of non-DoD US Government Missions that have been analyzed in this research.

FAA National Airspace System (NAS)
The NAS is a complex system of systems integrating the control of manned and unmanned aircraft and rocket launches and landings in the US airspace. The next generation NAS is to scale to the increased number of objects in the airspace. The process for engineering the NAS is documented in the NAS Systems Engineering Manual driven by mission analysis to identify capability shortfalls and then engineer solutions to address the shortfall.

NASA Journey to Mars
NASA has a mature mission planning and development capability for engineering the journey to Mars, with experience in integration of spaceflight elements that spans across systems, vehicles, and programs, as well as government, industry, and international partners. Mission development capabilities include:
- Product development and verification, including mission timelines, flight rules, and crew and ground procedures
- Analysis and modeling of vehicle performance, consumables and human / vehicle interfaces
- Flight design of launch, orbit, and entry flight trajectories and associated risk controls
- Operations tools design, development and testing, including onboard and ground software
- Mission readiness assessments
- Safety and Risk Assessment.

2.1.3 NATIONAL MISSION INITIATIVES (US AND NON-US)

The following are several examples of US and Non-US National Mission initiatives that have been analyzed in this research.

Critical Infrastructure Protection and Recovery

The theme of the December 2016 issue of *INSIGHT* magazine for systems engineering practitioners published by INCOSE and Wiley was "critical infrastructure protection and recovery." Infrastructure for electric power, communications, water, wastewater, transportation, oil and gas pipelines, and manufacturing supply chains are systems of systems. The issue of *INSIGHT* addressed the vulnerability of infrastructure to high impact threats such as space weather, electromagnetic pulse, cyber attacks, and physical attacks. The emphasis is to mission engineer infrastructure SoS to be resilient to such attacks.

Australian Land-Force Capability Integration

Australian Land-Force Capability Integration addresses the system of systems integration challenges, also called cross-project integration, facing the organization of Australian defense forces. These challenges include the integration of interoperable communication, command and control, and support systems between various platforms which link, for example, the Landing Helicopter Dock with air support, amphibious watercraft, support ships, and land forces, in order to provide the overarching amphibious capability. The objective is to realize the networked force described in the 2009 Defense White Paper: 'Defending Australia in the Asia Pacific Century: Force 2030', and also considering the Australian net centric warfare roadmap and the ISR roadmap. The Australian program leverages the US DoD SoSE approach, but is tailored to Australia's approach to defense matters. An important recognition is that SoS test and evaluation has fundamentally different goals, character, and intent than standalone system acquisition test and evaluation.

UK Remotely Piloted Aircraft (RPA) Operations

The UK term for mission engineering is 'capability engineering'. The UK Ministry of Defence (MOD) has similar experiences in the engineering, acquiring, and operating of their RPA system as described by Mindell (2015) for US RPA operations. Similar to US experiences, the challenges are in the composition and integration of disparate command, control, communications, and operations assets constrained by protocols and end-to-end latencies.

2.1.4 CRITICAL AREAS FOR ADDITIONAL RESEARCH IN MISSION ENGINEERING IDENTIFIED FROM OPEN SOURCE LITERATURE

There were three areas that the RT-171 team identified in the open source literature that are critical to achieving the desired capabilities in the context of real-world operations:

1. Non-determinism of real-world phenomena – the techniques and tools to perform mission analysis and engineering appear to be deterministic in nature; the real world is

quite the opposite (Deiotte and Garrett 2013) (Marvin, Whalen, Morantz, Deiotte, and Garrett 2014).

2. Explicitly accounting for systems operational availability $A_o < 1$, where A_o is the operational avaiablilty of a mission system, in real world scenario this is rarely "1". A relevant example is the operational availability of the integrated system of systems for Predator, Gray Eagle, and Reaper remotely piloted aircraft (RPA) operations (Mindell 2015).

3. Explicitly accounting for the human operators and commanders in the loops of the systems of systems – human beings require time to sense, think, interact, and decide that impacts the theoretical performance of systems of systems. Again, a relevant example is the PEST (political, economic, societal, and technological) factors on effectiveness of RPA operations (Mindell 2015). A non-defense example is the landing of US Airways Flight 1549 in the Hudson River between New York City and New Jersey on January 15, 2009 after a bird strike resulted in the shutdown of both engines. Initial analysis of the National Transportation Safety Board (NTSB) replaying the flight on simulators indicated that the aircraft could have made an emergency landing back at LaGuardia Airport or at Teterboro Airport in New Jersey. The flight simulator scenarios did not account for the time for the aircrew to assess what happened, understand the state of their aircraft, and regain situational awareness. Factoring in the latency of the aircrew in the simulators gave the result that an emergency landing at LaGuardia or Teterboro was not viable.

Mission engineering is an emerging discipline and the limited availability of references in these areas (items 1-3 above) seems to be evidence of that.

2.2 DEFINING MISSION ENGINEERING

According to the US Department of Defense (DoD), mission engineering is defined as:

> ***The deliberate planning, analyzing, organizing, and integrating of current and emerging operational and systems capabilities to achieve desired warfighting mission effects.*** (Gold 2016 and Defense Acquisition Guide 2017)

Aside from the defense domain, the definition of mission engineering expands to other domains as well. Butler and Woody (2017) defined mission engineering as understanding and documenting end-to-end execution of a mission to understand how all the SoS parts work together.

In the "Mission Engineering Integration and Interoperability" article by Moreland (2015), he expanded the definition of mission engineering as "planning, analyzing, organizing, and integrating current and emerging operational concepts for the purpose of evolving the end-to-end operational architecture and capability attributes, across the Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel and Facilities (DOTMPLF) spectrum, including anticipated Blue Force (BLUFOR) and Opposition Force (OPFOR) behaviors, that are

needed to inform the communities of interest involved in fulfilling mission needs statements". Moreland (2015) described mission engineering as "a systematic, quantifiable, and iterative approach for assessments of naval technologies, systems and capabilities with a system-of-systems (SoS) approach that combines the structure of Systems Engineering and the tactical insights of operational planning".

On December 9, 2010, the Chief of Naval Operation's (CNO Integration and Interoperability (I&I) Summit was briefed on a new collaborative approach to provide proactive sequential steps for I&I activities for functional end-to-end accountability. This new approach incorporates finding the gaps in current capabilities (Warfare Capability Baseline), developing solution recommendations to find the operational shortfalls (Capability Solution Management), and processing the results for approval, execution, and implementation within the Navy (Moreland, 2015). Figure 2 illustrates the new approach for I&I sequential activities that associates mission engineering and traditional SE within the 'V' model as time evolves.
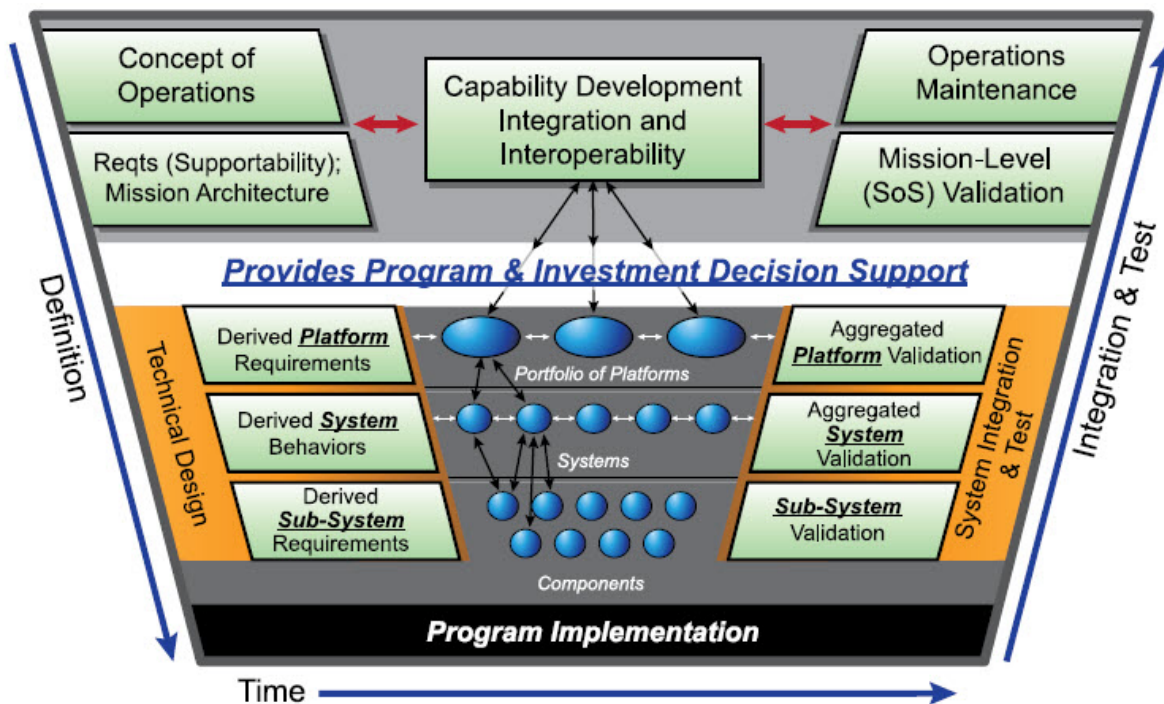
Figure 2: Mission Engineering within the Systems Engineering 'V' Model (Moreland 2015)

It is important to differentiate the definition of mission for NASA from the US DoD. According to the NASA Systems Engineering Handbook, a mission is defined as "a major activity required to accomplish an Agency goal or to effectively pursue a scientific, technological, or engineering opportunity directly related to an Agency goal. Mission needs are independent of any particular system or technological solution" (NASA, 2016). The NASA Mission Engineering and Systems Analysis Division (MESA) at Goddard Space Flight Center uses the term mission engineering in the application of engineering for space missions. The NASA MESA Division "provides end-to-end mission systems engineering and guidance, navigation, and control capabilities and technology development to conceive, design, analyze, implement, verify and validate on orbit,

and to support advanced scientific instruments and support platforms for ground-based, suborbital, and orbital science and exploration missions" (NASA 2017). NASA requires a mission engineering team (i.e. operations, space segment, scientist, and ground systems engineer) that uses the mission engineering process to prioritize the mission and science operations in a structured form in the early development phase. According to an earlier definition of mission engineering by NASA, mission engineering is "fundamentally a process improvement concept that addresses the interactions between the main mission elements of space, ground, operations, and science" (Ondrus and Fatig 1993).

Mission engineering is different from systems engineering because the individual systems that are part of the military capability, such as ships and aircrafts, are inherently flexible, functionally overlapping, multi-mission platforms that are supported by a complex backbone of information communication networks. Several other allied nations were found also to describe mission engineering as capabilities engineering or force design. Capabilities engineering is explained in the Literature Review (Appendix D).

2.2.1 MISSION ANALYSIS

Mission analysis is performed to "understand a problem or opportunity, analyze the solution space, and initiate the life cycle of a potential solution that could answer the problem or take advantage of an opportunity" (SEBoK 2017).

Mission engineering differs from mission analysis in that the latter only addresses examination of current operational and system capabilities and not the design and engineering to assure the mission. In reference to mission analysis, a modified response to Blanchard and Fabrycky (2011) define mission as an "examination and definition of the primary and secondary purposes of a system".

2.2.2 CAPABILITY ENGINEERING

The term capability is widely used across many industrial sectors and has begun to take on various specific meanings across, and even within, those sectors. Terms such as capability-based acquisition, capability engineering and management, life capability management, capability sponsor, etc. are now ubiquitous in defense and elsewhere. Henshaw et al. (2011) have identified at least eight worldviews of capability and capability engineering and concluded that the task of capability engineering is not consistently defined across the different communities.

Whilst most practitioners recognize that there is a strong relationship between capability and system of systems (SoS), there is no agreed upon position. However, there are two beliefs that are widely accepted among the different communities, including:

- a capability comprises a range of systems, processes, people, information and organizations. (i.e. a system at levels three through five in Hitchin's (2003) five layer model, such as a Carrier-Strike capability) and
- the capability is a property of the SoS (i.e. the capability of Carrier-Strike to engage targets within 300 miles of the sea), which may be emergent or designed.

2.2.3 SERVICES VIEW OF SYSTEM OF SYSTEMS ENGINEERING

The *Guide to the Systems Engineering Body of Knowledge* (SEBoK) has the following to say about service-oriented systems of systems (BKCASE Authors 2017):

"A system of systems (SoS) is typically approached from the viewpoint of bringing together multiple systems to provide broader capability. The networking of the constituent systems in a SoS is often a key part of an SoS. In some circumstances, the entire content of a SoS is information and the SoS brings together multiple information systems to support the information needs of a broader community. These information technology (IT)-based SoS's have the same set of characteristics of other SoS's and face many of the same challenges such as constituent systems havin their own purposes, priorities, and goals; possibly being outside the scope of control of the SoS, requiring reliance on influence; and asynchrony due to differnet lifecycles of each constituent system. Currently, IT has adopted a 'services' view of this type of SoS and increasingly applies a International Organization for Standardization (ISO) 20000 series (Information technology -- Service management) or Information Technology Infrastructure Library (ITIL) v. 3 (OGC 2009) based approach to the design and management of information-based SoS. A service perspective simplifies SoSE as it:
- is a more natural way for users to interact with and understand a SoS,
- allows designers to design specific services to meet defined performance and effectiveness targets, and
- enables specific service levels to be tested and monitored through life.
- Although it has not been proven to be universally applicable, the services view works well in both IT and transportation SoS."

2.2.4 INTERVIEW RESULTS ON THE DEFINITION OF MISSION ENGINEERING BY INDIVIDUAL PARTICIPANTS

The RT-171 team's qualitative analysis is derived from 32 interviews with subject matter experts and practitioners who are involved with mission engineering work. Each interview is conducted in no more than 60 minutes and the questions are categorized in three main sections, namely mission engineering, competencies, and future directions. The sample of interview questions can be found in Appendix C. The first section of the interview questions

begins by requesting the participants to provide their definition of mission engineering and also their organization's philosophy, processes, and approaches in mission engineering. The following figures provide the aggregated findings based on the interview responses and the subtitle shows the interview question that corresponds to each analysis. On the charts, the red bar represents the percentage of interviewees and the blue bar represents the percentage of excerpts based on the interview transcripts.

Figure 3 shows the categorization of participants' varied responses on the definition of mission engineering with a percentage of excerpts based on the percentage of interviewees. All the interview participants responded to this question. None of the interview participants said that mission engineering is a different discipline from systems engineering, although two of them described some of the differences between mission engineering and systems engineering. The variations in responses ordered from most frequent to least frequent are as follows:

- Mission engineering is systems engineering including some additional activities (referred to as "ME is SE+" in Figure 3,
- Mission engineering is system(s) of systems engineering,
- Mission engineering is systems engineering, and
- There are differences between mission engineering and system engineering.
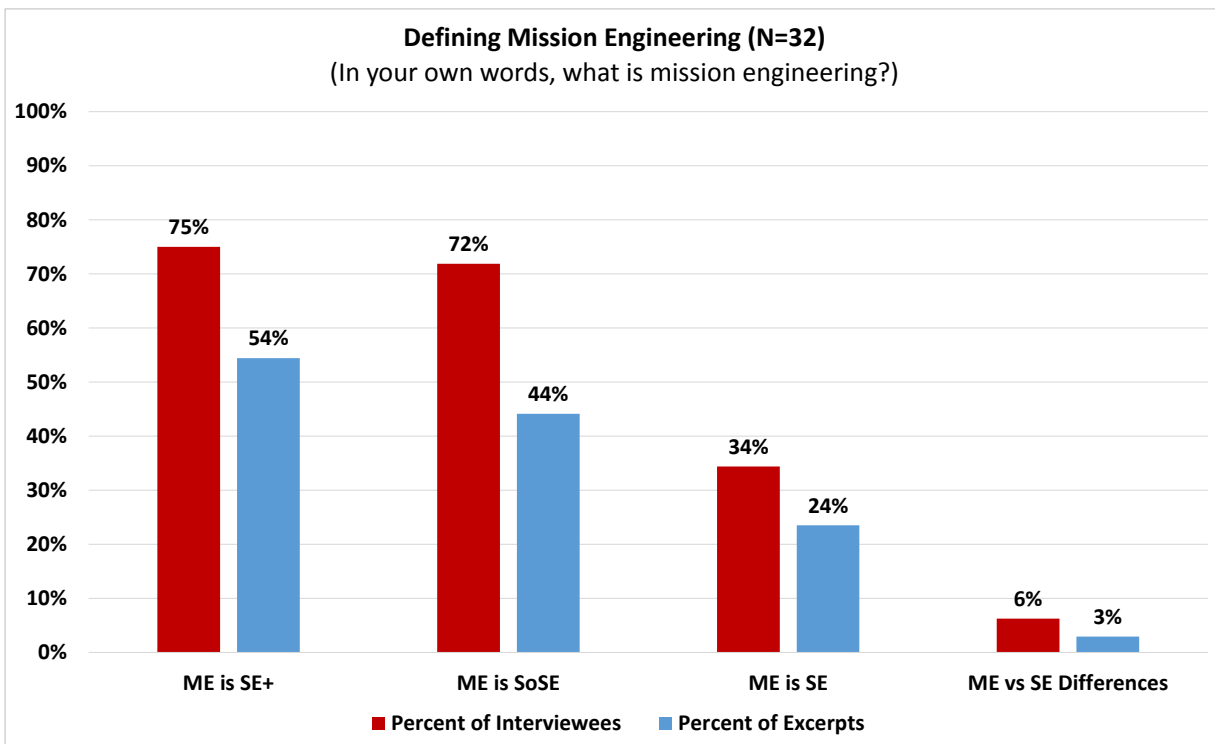
Figure 3: Percentage of Excerpts and Interviewees Based on their Definitions of Mission Engineering

Based on the interview responses, the following are some direct quotations on their definitions of mission engineering. A couple of the interview excerpts for **"ME is SE+"** are cited as:

- "It takes holistic thinking one step further. In SE, parts are important as it relates to the whole. To complete a mission can only be accomplished through extension or scaling of SE."

- "My definition is based on my mission based on the capability to support specific missions. Want to make sure I have full end-to-end systems engineering disciplines to engineer, design, test, and validate for that capability."

Some of the interview responses for **"ME is SoSE"** are as follows:

- "I view ME as the ability to understand a collective set of systems and treat them as SoS, how they relate to and interrelate to one another and how they can be modeled and designed."

- "Make sure mission essential functions (mission threads, mission critical functions) are accomplished across all systems, including SoS, and in many cases operations function."

Some of the interview excerpts for **"ME is SE"** are as follows:

- "Mission engineering (ME) is SE as applied to design and the integration of kill chains."

- "ME is SE as applied to solving the mission."

The interview response for **"ME vs SE Differences"** is as follows:

- "Sometimes, SE may miss the mark because it didn't have the relationship with the operation."

Figure 4 shows the percentage coverage on the overall definition of mission engineering coding by the organization or service based on the NVIVO qualitative analysis software. Both the Navy and Army provided the most coverage compared to other organizations, which is reasonable given the majority (66%) of the interview participants were from the Services.

Excerpts Percentage on the Philosophy of Mission Engineering by Organization Type
(N=32)
(What is your organization's philosophy on mission engineering?)
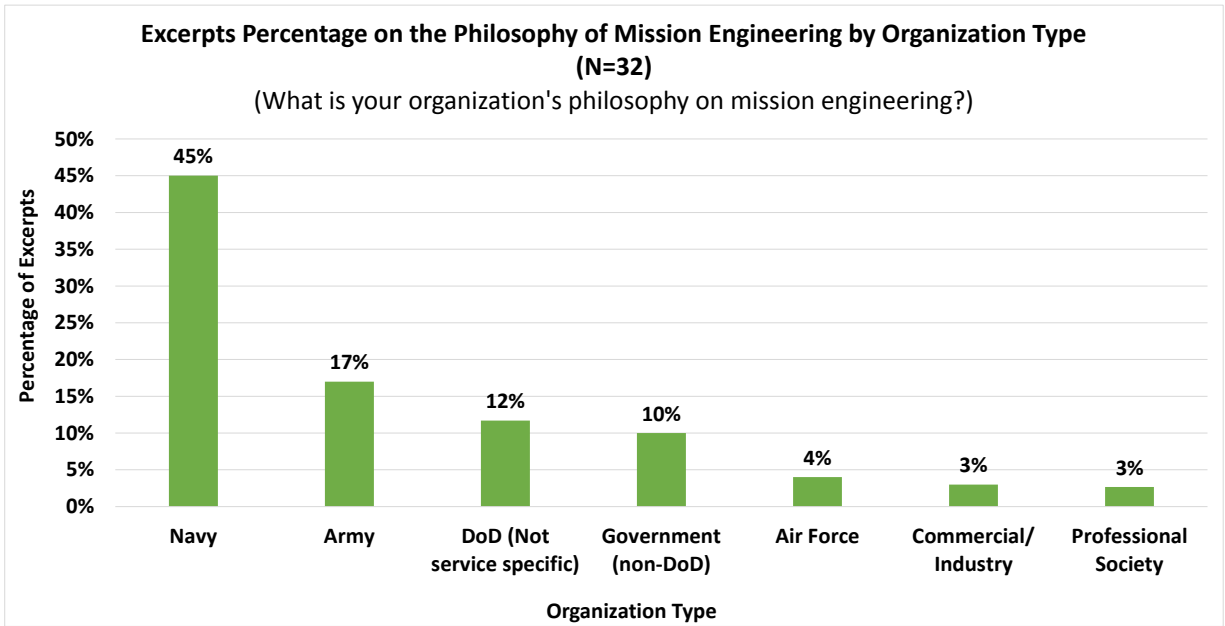
Figure 4: Percentage of Excerpts on the Definition of Mission Engineering by Organization Type

While the most frequent interview responses considered mission engineering as an extension of SE, Figure 5 depicts the coding by organization or service. The interview responses from all the participating organizations have a general understanding that mission engineering is an extension of systems engineering and considered as SoSE. Figure 5 indicates that the Navy has a clear understanding on the definition of mission engineering, and could be attributed to the early developmental work on mission engineering I&I by the Navy.
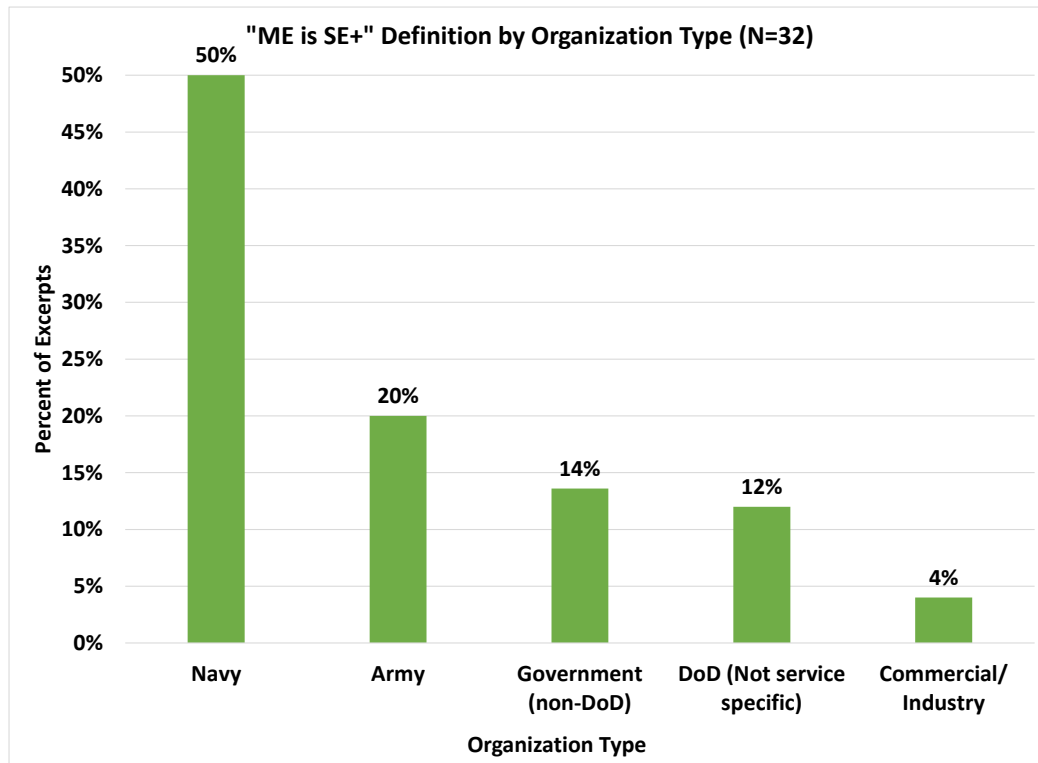
Figure 5: Interview Response: "ME is SE+" Coding by Organization Type

The interview responses for the participants' definition of mission engineering are compared with the definitions of mission engineering that we found from our literature review. More than half of the participants defined mission engineering as an extension of SE and considered it as SoSE, which aligns with the definitions of mission engineering provided by the US DoD, Navy, NASA, and other sources. None of the participants mentioned that mission engineering is completely different than SE, although one of the participants mentioned differences between mission engineering and SE. There is a clear link in the data between SE and mission engineering. There is not universal agreement on how the two are related and interview responses about the distinctions are situational.

2.2.5 INTERVIEW RESULTS ON THE ORGANIZATION DEFINITION AND PHILOSOPHY ON MISSION ENGINEERING BY INDIVIDUAL PARTICIPANTS

The participants in this study revealed their perspectives on their respective organization's definition and philosophy on mission engineering. Figure 6 depicts the interview participants' perceptions and understanding of their organizations' definition and philosophy on mission engineering, which can be summarized as:

- A comparison between the interviewees own definitions (Figure 3) with their organizations' definitions of **"mission engineering is system of systems engineering"** indicates that *their philosophy is aligned with their organizations*

- The participants considered their organizations' **understanding of the operational context** as the main philosophy on mission engineering
- Fifteen percent of them said their organizations have no definition or philosophy, followed by some that indicated their organizations generate minimum effort to meet mission objectives
- A minimal amount of interview participants perceived their organizations as being confused with the different definitions, and some even considered ME as out of their organizations' scope
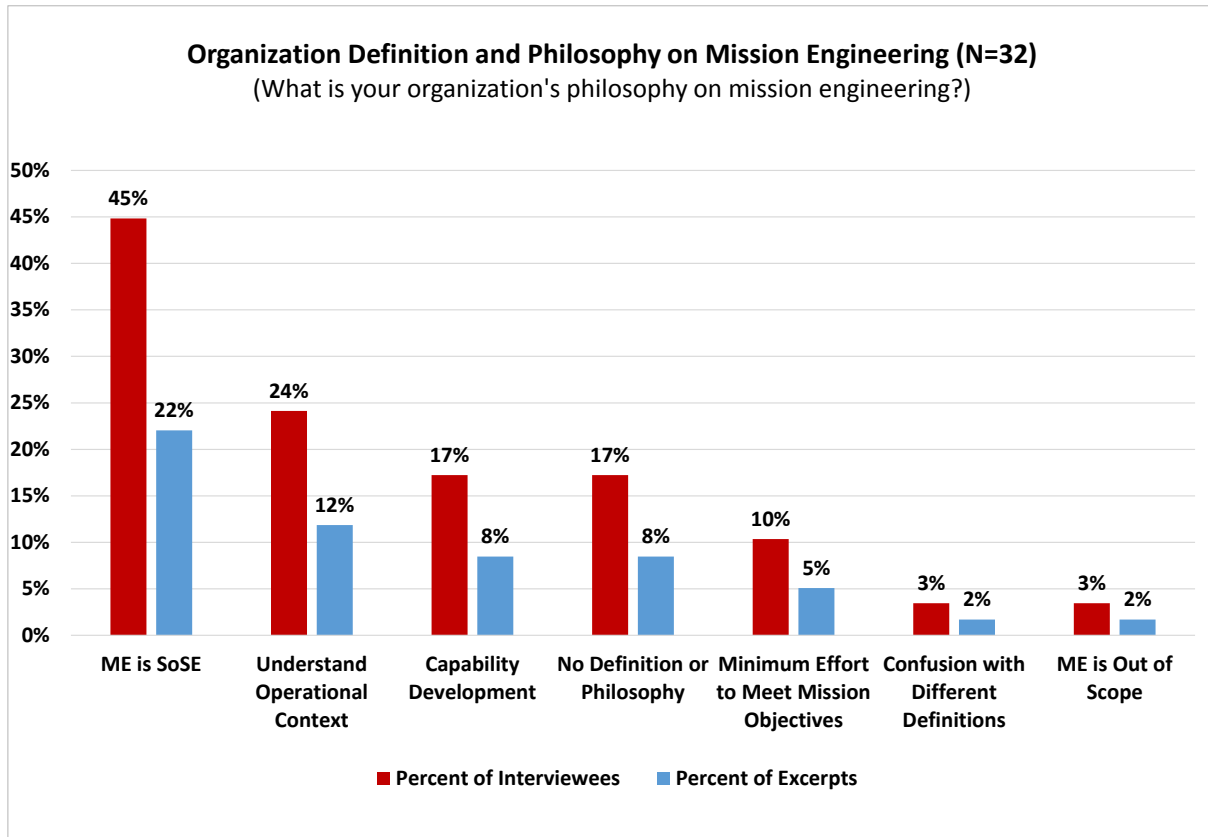
Figure 6: Perspectives on the Organization Definition and Philosophy on Mission Engineering

Based on the interview question "What is your organization's philosophy on mission engineering?", the following interview excerpts were extracted and some were redacted to protect the participants' privacy and confidentiality, as shown in Table 3.

Table 3: Selected Interview Excerpts on the Organization's Definition and Philosophy on Mission Engineering

Mission Engineering Activities	Interview Excerpts
ME is SoSE	• "From ME perspective, yes there is a philosophy, from my organization's perspective. So what I do is system of systems engineering and integration for the organization's network and any technology insertion into the organization."
Understand operational context	• "Using systems engineering (SE) processes with a different perspective. Apply SE processes in two different perspectives – in platform and looking more holistically across organizations. The processes were applicable in establishing concept of operations (CONOPS) for customers and looking at them to determine CONOPS to be effective, and the platforms needed to perform them."
Capability development	• "We break down the process. When we're supporting mission gaps, we take that capability gap; all stakeholders are identified, what the requirements are, broken down into stakeholders and information exchange requirements and how the information exchanges are done." • "Mission systems engineering is the analysis to understand the network or capability you're designing will enhance the soldiers' mission. You can build all the arch you want but they are only pictures. Analysis will inform you. Analysis early enough. So much new technology – have different levels of fidelity of analysis. You might have to go with lower fidelity models for that. That's the most important/critical piece." • "Doing mission analysis and business analysis are all part of it. We're driven to do mission and business analyses in a set of processes in INCOSE and ISO."
No definition or philosophy	• "I'm not sure if we have a philosophy." • "I don't think I've heard from them."
Minimum effort to meet mission objectives	• "Minimum requirements to meet the mission objectives." • " Struggling with that but looking at the operational context, COCOM (Combatant Command), giving more context to where the mission is heading to. Haven't trickled down to the system and technologies levels. Struggling to reach consensus and transient. No one wants to champion and take ownership."
Confusion with different definitions	• "Always been confusing. A lot of people have different definitions. First, this is not clearly understood by the workforce, program offices, and as a result, don't get funding."
ME is out of scope	• "Mission engineering is constrained within the bounds set by a program. The scope of the program may not take a mission-oriented approach. And the program provides the money."

2.2.6 RESEARCH FINDINGS ON THE SCOPE OF MISSION ENGINEERING

This section begins by reporting the critical activities within the scope of mission engineering based on the interview participants' positions, key responsibilities, and key value provided. The participants provided insights that are crucial in the mission engineering activities. Figure 7 shows the interview responses analysis on the critical activities in mission engineering, which can be summarized as:

- Critical *mission-focus* activities begin first and foremost, with an **understanding of the mission** as the highest overall compared to other activities, indicated by the highest percentage of interview participants

- *Top technical activities* include the architecture, analysis, requirements, modeling and simulation, capability development, integration and interoperability, testing and evaluation, technical assessments, and composition – all of which are recognized as difficult in a complex mission environment

- Other *non-technical activities* include communication, workforce development, and uncertainty when dealing with mission engineering work

Mission Engineering Activities (N=32)
(Please describe your current position. What are your key responsibilities? What is the key value you provide in this position? What is the most critical thing you do to be effective in your current position?)

Activity	Percent of Interviewees	Percent of Excerpts
Understand the Mission	56%	11%
Architecture	50%	11%
Analysis	38%	8%
Requirements	34%	7%
Modeling & Simulation	28%	6%
Capability Development	28%	6%
Integration & Interoperability	22%	6%
Testing & Evaluation	22%	4%
Communication	22%	4%
Workforce Development	16%	3%
Technical Assessments	9%	2%
Uncertainty	9%	2%
Composition	9%	2%

Figure 7: Mission Engineering Critical Activities

To provide more detailed activities in mission engineering, selected interview excerpts are listed in Table 4. Some interview excerpts are redacted to protect the participants' privacy and confidentiality.

Table 4: Selected Interview Excerpts on Critical Activities in Mission Engineering

Mission Engineering Activities	Interview Excerpts
Understand the mission	• "Understand the mission. We need people that understand the warfighting environment. We need someone who understands the reality of the war."
Architecture	• "The mission analysis and mission architecture competencies are important to performing ME." • "Architecture-centric analysis process for looking at things from mission engineering point of view."
Analysis	• "We break down the process. When we're supporting mission gaps, we take that capability gap; all stakeholders are identified, what the requirements are, broken down into stakeholders and information exchange requirements and how the information exchanges are done." • "Mission systems engineering is the analysis to understand the network or capability you're designing will enhance the soldiers' mission. You can build all the arch you want but they are only pictures. Analysis will inform you. Analysis early enough. So much new technology – have different levels of fidelity of analysis. You might have to go with lower fidelity models for that. That's the most important/critical piece." • "Doing mission analysis and business analysis are all part of it. We're driven to do mission and business analyses in a set of processes in INCOSE and ISO."
Requirements	• "The requirements flow-down and understanding what's required to translating to requirements to meet the needs is a critical piece." • "The integration with SE and ME meet at the requirements. SE requirements management and elicitation should be critical to where they meet."
Modeling & Simulation	• "Agent-based simulations in the operational context. There is opportunity to put in the joint fleet exercise groups. We take operational threads and kill-chain and build an agent for everyone, and build a high-fidelity model with behaviors. We run simulations to capture emerging behaviors. It can predict what things should look like." • "We use Model Based Systems Engineering (MBSE), SysML, and other engineering tools on a timeline to have a complete functional flow block diagram (FFBD) and concept of operations (CONOPS). Iterate

Mission Engineering Activities	Interview Excerpts
	until all the functions work together - functions, products, what they need to do, breakdown functions, understand the interfaces from one function to another."
	• "Emergence of computational simulations – era of big data. Big data in the commercial sector usually has lots of consumer data to use - we don't have that luxury. But we're building on that to gather more data. Sometimes decision makers oversimplify but really they need to consider the full hierarchy."
Capability Development	• "Looking at the overall capability of systems engineering. There is systems engineering and there is system of systems engineering (SoSE). Systems engineering is building a weapon system. SoSE is putting the weapon system into the whole picture."
	• "We are initiating efforts to plan future capabilities and close gaps at the mission domain level."
Integration & Interoperability	• "We took the bits and pieces and the kit we had and knit them together into something useful for the warfighters."
	• "I think the best simplest description I have is mission engineering is about connecting the Lego pieces in a way that will support a particular mission. It's not about deciding whether to go with Lego or K'nex and it's not about buying the pieces. It's the end of the development process. How can I best satisfy my customer's needs with what I have?"
	• "The most critical thing we do is the integration of information. That's key for spearheading this."
Testing & Evaluation	• "Testing at larger system of systems (SoS) to confirm if they can meet the requirements."
	• "Test mission threads."
	• "Testing toolset is essential too."
Communication	• "Communication especially with the parts and pieces that goes into testing (professional and technical). Get right information to the right people."
	• "Try to attend all the technology reviews that I can to provide the Program of Records whether they can use it or not, to give them the knowledge if they can move things forward."
Workforce Development	• "I would like to see a process for the development of the operational skillset. Something like a rotation or internship to get them into the Fleet command and/or exercises, to see all the things that encompasses a mission. In terms of management, engineering, and systems engineering, we've got all the programs and cohorts for

Mission Engineering Activities	Interview Excerpts
	operational experience. Not a course for average acquisition personnel but for those in the ME path, it would be invaluable."
Technical Assessment	• "Need to ensure all the right players are involved to analyze the full set of technological and operational solutions so that the analyses and decisions are "fully-informed" at all security levels." • "I am focused on the materiel solution. The outcome is meeting the technical performance."
Uncertainty	• "Being able to predict the future and what it is that you want so you can clearly ID the mission systems engineering that you need to support that. We might know something for 3 years out but by the time we get there, it's changed. Constant, evolving unknowns."
Composition	• "One of the things we developed was a series of ways something could fail and patterns for how to design a service. We developed patterns for composition." • "Because we believe in the universality of the system, we treat it as mission effectiveness, true bounding at the level."

The interview data also points to the lack of factoring non-determinism in current mission engineering work, as shown in the literature review analysis and follow-ups on private, deep background conversations. Since mission engineering work is relatively new, the question about the mission engineering processes and practices were posed to the interview participants. Figure 8 shows the analysis of the interview responses to the question on their organizations' current processes and practices in mission engineering, which can be summarized as:

- *Understanding the operational context* was deemed as the most important step in the processes and practices in mission engineering, followed by an understanding of the capability and adherence to military standards in order to identify gaps in their capabilities of the overall mission

- The **SE technical processes** such as architecture, modeling and simulation, interoperability, and feasibility analysis were applied in mission engineering, within a continuous feedback

- The **non-technical** practices and processes were discussed when term "coalition of the willing" was invoked twice as being a part of the mission engineering practices, as well as the acquisition process as being influential in mission engineering.

Processes and Practices in Mission Engineering (N=32)
(What is your organization's process or approach to performing mission engineering?)

Process/Practice	Percent of Interviewees	Percent of Excerpts
Understand Operational Context	42%	12%
Architecture	35%	12%
Understand Capability	35%	12%
Identify Gaps	19%	8%
Modeling & Simulation	10%	3%
Acquisition	6%	3%
Standards	6%	3%
Interoperability	6%	3%
Coalition of the Wiling	6%	2%
Continous Feedback	6%	2%
Feasibility Analysis	6%	2%

Figure 8: Processes and Practices in Mission Engineering

Table 5 provides some interview excerpts based on the question "What is your organization's process or approach to performing mission engineering?". Some interview excerpts are redacted to protect the participants' privacy and confidentiality.

Table 5: Interview Excerpts on Processes and Practices in ME

Processes and Practices in ME	Selected Interview Excerpts
Understand operational context	• "Work with Fleet to understand their operational needs and translate them into requirements that the technical community can understand." • "A lot of this would be simple steps of processes and rules – combine with systems engineering to do design activities for processes and technologies to think of architecture design, management processes, operational customer needs, business needs perspective."

Processes and Practices in ME	Selected Interview Excerpts
Architecture	• "The operational architecture includes all mission types of functions and the mission architecture connects with the system architecture and operational architecture." • "Architecture-driven analysis is a process that's been ongoing in our organization." • "We develop architecture products to understand the system and how to employ capabilities in an exercise where there's holes or gaps."
Understand capability	• "We tailor a high level systems engineering mission that starts with being able to understand the roadmap of where our organization needs to go and go out as far as we can where we have clarity of on. Work across community to understand capability and ability to understand capability by certain timeline." • "Map out space and look at capability to look for gaps and make a decision if we need to change anything."
Identify gaps	• "Identify gaps in capability and change. In the long term, I may look at new technologies, and how it can impact and close gaps. It may not be tied to any programs." • "The problem with mission needs and programs is, how do you close the gaps? There is no administrative control."
Modeling & simulation	• "Using a model-based approach to define and manage the process end-to-end. They use architecture as a framework in the Navy to manage the mission thread but also as a systems model to define requirements, definite analyses, and manage behaviors throughout the lifecycle."
Acquisition	• "We collect and validate the data and see if the instrument is good enough for the government to purchase."
Standards	• "It is more than military standards, e.g. electromagnetic pulse (EMP) standards, but military standards are there for sure. For example: protection (documentation requirements) - use as core requirements that need to be adhered to."
Interoperability	• "Bringing together diverse domains (undersea, land, space, etc.) to be integrated to meet the needs of the mission through joint operations platforms, key technologies and risk maturity to determine the operational needs."
Coalition of the willing	• "Some programs see the benefit upfront (coalition of the willing)." • "For gaps in standards, clarifying these standards can be difficult and may impact the baseline. "Coalition of will" insure systems is fulfilling its role in SoS."

Processes and Practices in ME	Selected Interview Excerpts
Continuous feedback	• "Allows me to adjust architecture based on feedback and we continue that process so we get to the capability that the Army approves then work the tail end of how to field that capability." • "Continuous feedback loop."
Feasibility analysis	• "Look at alternate course of actions to address the capability gap, to include feasibility analysis based on the stakeholder's feedback and feeding back to the organization."

To enrich the mission engineering body of knowledge, 31 of the participants were asked to determine if there was any overlap between mission engineering and SE based on their activities. Figure 9 displays the results where an overwhelming majority of the participants indicated that there is overlap between ME and SE work. Only one of the participants said that there is no overlap between mission engineering and SE in the individual's work experience.
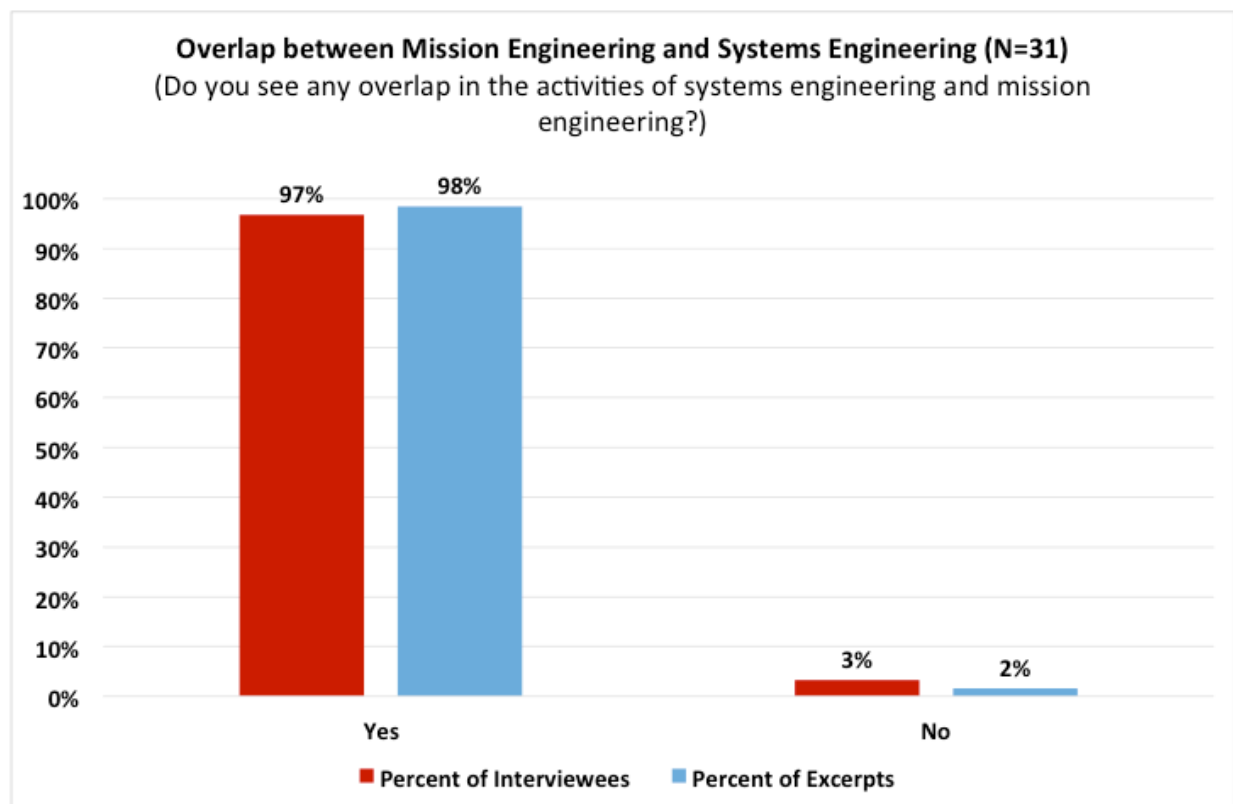
Figure 9: Interview Responses on the Overlap of Mission Engineering and Systems Engineering

Figure 10 shows the interview responses for those who indicated that there is an overlap between mission engineering and SE to better understand what they are. The majority

considered mission engineering as a form of SoSE. In regards to this question, the other responses include:

- Mission engineering and systems engineering are interchangeable,
- Mission engineering is a subset of systems engineering, and
- Mission engineering is an extension of systems engineering.
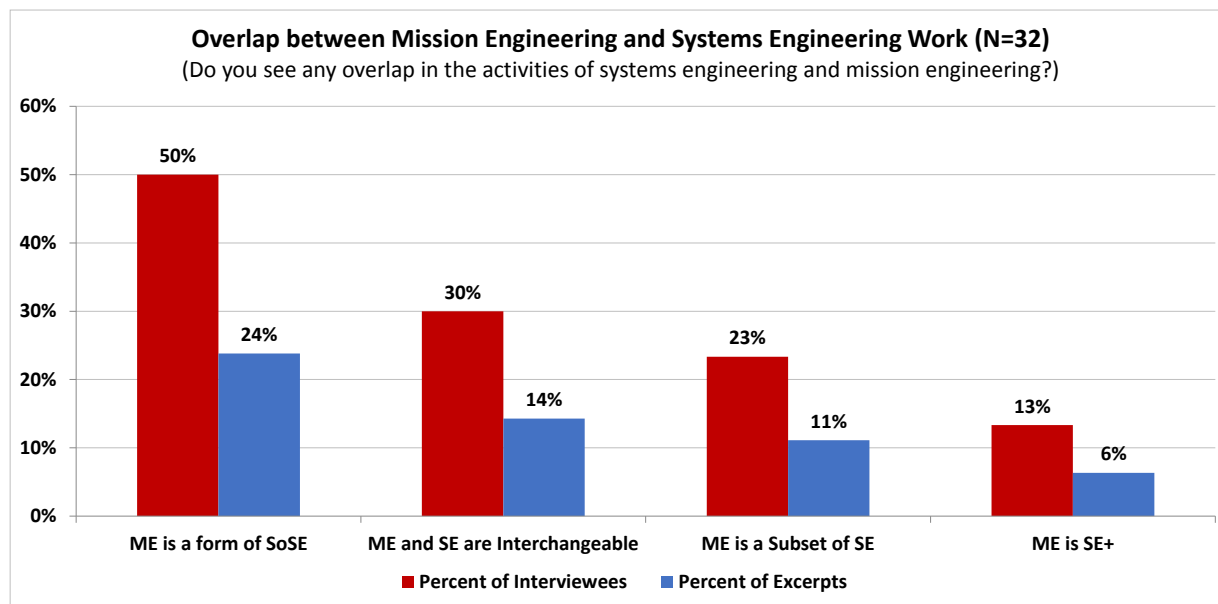
Figure 10: Interview Responses from those who indicate that there is Overlap between Mission Engineering and Systems Engineering Work

Table 6 provides some interview excerpts based on the question "Do you see some overlap in the activities of systems engineering and mission engineering?". Some interview excerpts are redacted to protect the participants' privacy and confidentiality.

Table 6: Selected Interview Excerpts on the Overlap between Systems Engineering and Mission Engineering

Overlap between SE and ME	Selected Interview Excerpts
ME is a form of SoSE	• "Mission engineering is a form of system of systems engineering (SoSE).Take systems engineering practices and apply to more complex problems. When you view the system with the built components, then systems engineering practices makes sense."
ME and SE are interchangeable	• "I think ME is SE for me. I think a system can be defined as a part, system, weapon system, SoS or how it's defined as a mission is the system. It's a different perspective but the fundamental precepts of SE still apply – it's a perspective of how you view at a global or 10,000 feet level – mission as a focus."

Overlap between SE and ME	Selected Interview Excerpts
ME is a subset of SE	• "Absolutely. Mission engineering is yet another bucket in the multitude of systems engineering. Systems engineering is way too broad of a definition already but mission engineering fits within it."
ME is an extension of SE (ME is SE+)	• "ME is bigger and broader than SE. SE is about the solution. ME is about the operational requirements, solutions, and capability."

2.3 ACADEMIC PROGRAM IN MISSION ENGINEERING

According to the Worldwide Directory of Systems Engineering and Industrial Engineering developed by the Systems Engineering Research Center (SERC) at Stevens Institute of Technology and the International Council on Systems Engineering (INCOSE), there are 112 universities worldwide offering systems engineering academic programs (SERC, 2017). There are some universities that provide system of systems (SoS) curriculum (refer to Appendix E).

Based on our research, there is only one established mission engineering program. This academic program is a graduate certificate program from Old Dominion University (ODU) in Mission Analysis and Engineering. According to this ODU graduate certificate program, mission engineering is "an emerging discipline in which system-of-systems engineering tools and practices are combined with the tactical insights of operational planning" (ODU, 2017). The ODU program is designed with a focus on the U.S. Navy's operational needs and requirements. The learning objectives include "integrating the Fleet, Technology, and Acquisition communities to develop advances in warfighting capabilities across mission areas" (ODU, 2017).

The close proximity between the ODU-Dahlgren and the Naval Surface Warfare Center (NSWC) Dahlgren Division is geared for the local communities of interests, and allows practitioners to participate in the ODU Mission Analysis and Engineering graduate certificate program. One of the ODU adjunct professors who developed the ODU mission engineering curriculum and teaches one of the courses is Dr. James Moreland, SES, Deputy Director for Naval Warfare, Office of the Secretary of Defense Acquisition, Technology and Logistics. The ODU mission engineering curriculum can be found in Appendix F. The students take four courses including one required course, three electives, and a one-credit capstone course where the students apply the knowledge from the four courses through project-based learning.

Massachusetts Institute of Technology (MIT) started a short course in the summer of 2017 that is related to mission engineering titled, "Surface Ship Combat System Design and Integration". This course is classified SECRET/NORFORN, and is open to active-duty U.S. military, U.S. government employees, and U.S. civilian contractor personnel with U.S. government sponsorship. Accepted students are expected to have mature technical backgrounds based on their experience or education (equivalent to a graduate education). The one-week course was also developed by Dr. James Moreland with an objective of providing students with knowledge of surface ship combat systems and the factors that impact their integration among themselves and aboard ship, as well as the impact of missions and threats as they relate to platform and system design considerations. The MIT course covers topics such as:

- Introduction and Overview of Combat System Architecture,

- Mission and Requirements,

- Architecture for Ships and Combat Systems,

- Discussion of Specific Warfare Areas: Surface and Land Attack, Aegis and non-Aegis (AAW), and Ballistic Missile Defense,

- Integrating into Ship Architectures and Impact,

- Integrated Topside Design,

- Advanced Technologies, and

- Integration Challenges.

2.4 RESEARCH FINDINGS ON THE GAPS IN MISSION ENGINEERING

When the interview participants were asked about their perspectives on critical challenges in mission engineering, these challenges were identified as gaps in this study. Figure 11 shows the summary of the aggregated analysis on the critical challenges to better understanding the scope and context of mission engineering. To provide a detailed view, the interview responses were categorized into technical and non-technical challenges in mission engineering.
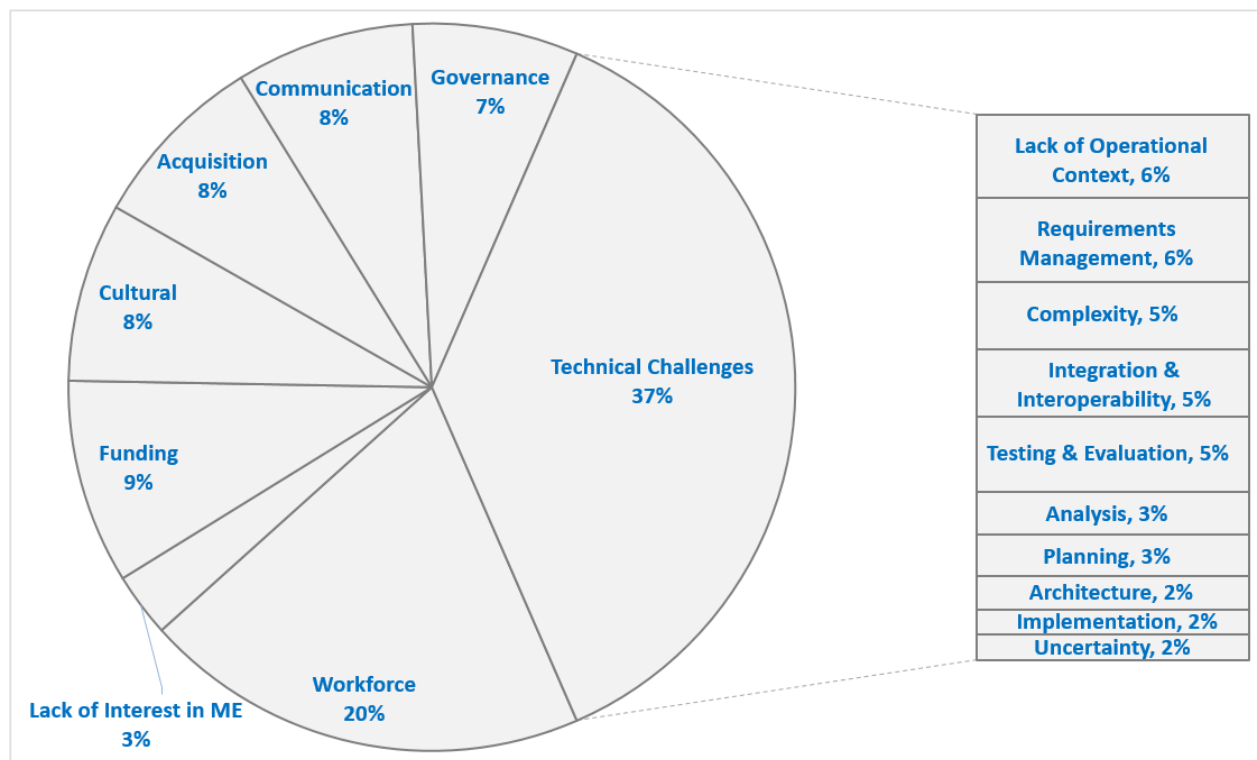
Figure 11: Summary of the Interview Responses on the Critical Challenges in Mission Engineering (N=32)

Figure 12 shows the interview responses analysis of critical non-technical implementation challenges in mission engineering. The top challenges are all related to ***non-technical implementation*** issues related to workforce, culture, funding, governance, acquisition, and communications, and lack of interest in mission engineering, with workforce being the highest overall challenge.

Non-Technical Implementation Challenges in Mission Engineering (N=32)
(What do you see as critical challenges in mission engineering?)

Challenge	Percent of Interviewees	Percent of Excerpts
Workforce	44%	20%
Cultural	41%	8%
Funding	34%	9%
Governance	34%	7%
Acquisition	31%	8%
Communication	31%	8%
Lack of Interest in ME	16%	3%
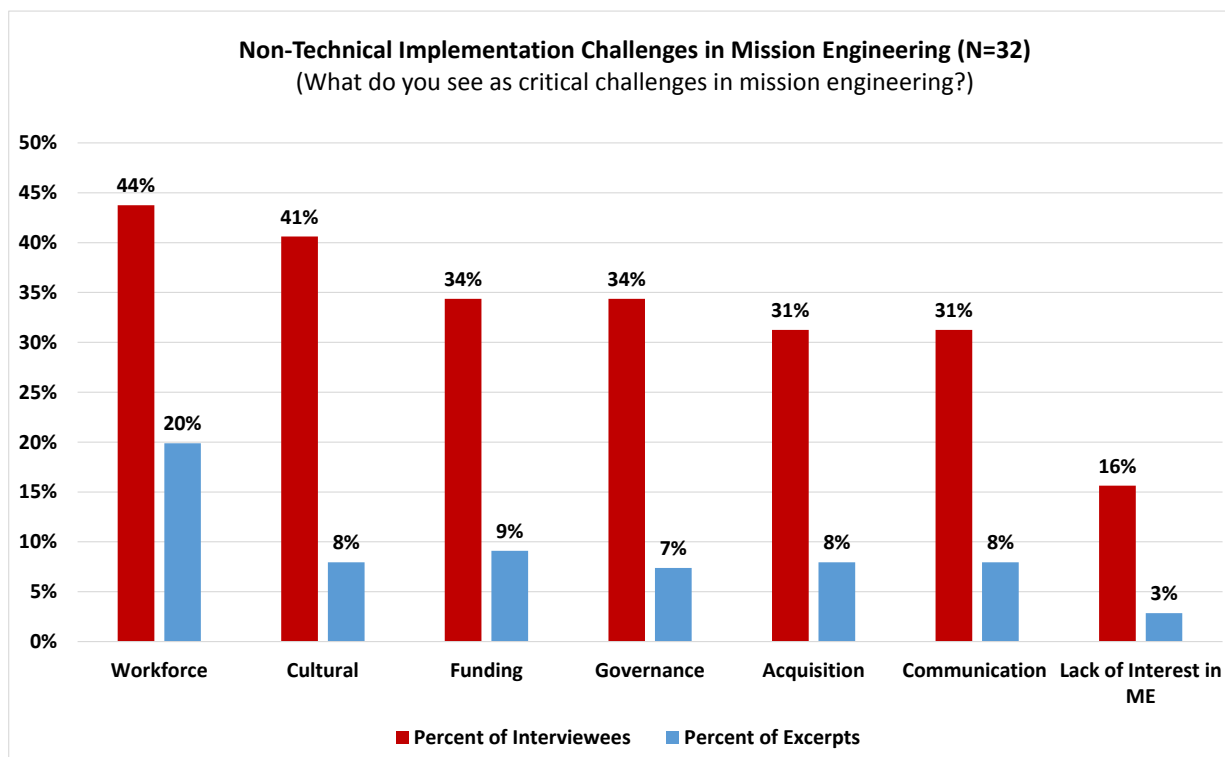
Figure 12: Critical Non-Technical Implementation Challenges in Mission Engineering

Some of the interview excerpts are selected to highlight the critical non-technical implementation challenges in mission engineering, as shown in Table 7.

Table 7: Selected Interview Excerpts on Critical Non-Technical Implementation Challenges in ME

Non-Technical Implementation Challenges	Selected Interview Excerpts
Workforce	• "I would say workforce development. Even if you get funding, there are very few people with expertise to do the work. There is only a handful." • "The skillset we need is what everyone wants. I don't know if we can attract them all. Competition in industry for that talent. Bring on folks with analytics skills – almost every industry is doing it." • "Since most have 25 to 30 years of experience in large systems, we essentially handpicked them. The problem is we don't have the up and coming engineers to assume the roles."

Non-Technical Implementation Challenges	Selected Interview Excerpts
Cultural	• "The #1 would be culture because we have an industry of people who have been doing things the same way for a long time. Getting people to embrace change." • "Provide more opportunities to self-assess and department investing in more mission environments. Unfortunately funding isn't approached like this right now – need a culture change."
Funding	• "You will never (with the current acquisition process) get SoSE funded because the phrase is " we fund systems, not SoSE". Even if ME bubbles up, it will be incredibly hard to find these products. We know they only fund systems. I have never seen funding for SoSE capability." • "Integrated capability list – but very broad and general because it's been underfunded."
Governance	• "In the implementation context by the U.S. DoD, the issue is by definition, the DoD is stove piped into services that have grown up into services that have gone from capability in battle spaces and fragments them. It fragments the stakeholders and governance. The fundamental issue is we try to overlap it in a governmental phase." • "Governance – how do you deal with it?"
Acquisition	• "The acquisition process is broken because the government has a hard time cutting across things. Acquisition capability is much more different – policy touches different systems." • "Get away from the stone-pipe nature of the acquisition process… Change the acquisition process and the way they get capability."
Communication	• "Improve communication across the board. Keep communication with Senior Leaders and communicate down to people down in the field to do their jobs so they understand and reap the benefits provided by science and technology." • "Communication and decision making when not having the right information. Sometimes data gets skewed. That's something that was dealt with."
Lack of interest in ME	• "Senior levels are unclear if ME is an old or new discipline, of if these are just buzz words. The danger or potential detractor (ex. program office) is the belief that it's materiel instead of maybe change in tactics. People are not buying into the general philosophy." • "Mission support in ME – the fact that you have to have or need joint buy-in that the process will help them at the service level, not just the joint level. Our real intentions is not taking away any capability, but rather looking from a mission success standpoint. It is critical to have everyone's buy-in."

Figure 13 shows the interview responses analysis of critical technical implementation challenges in mission engineering. The *top technical* challenges include those related to the operational context, requirements management, and testing – all of which are recognized as difficult in a systems oriented acquisition system.

Top Technical Challenges in Mission Engineering (N=32)
(What do you see as critical challenges in mission engineering?)

Challenge	Percent of Interviewees	Percent of Excerpts
Lack of Operational Context	25%	6%
Requirements Management	25%	6%
Complexity	25%	5%
Integration & Interoperability	22%	5%
Testing & Evaluation	22%	5%
Analysis	16%	3%
Planning	16%	3%
Architecture	13%	2%
Implementation	9%	2%
Uncertainty	9%	2%

Figure 13: Critical Technical Challenges in Mission Engineering

Table 8 lists some of the interview excerpts to highlight the critical technical implementation challenges in mission engineering.

Table 8: Selected Interview Excerpts on Critical Technical Implementation Challenges in ME

Critical Technical Implementation Challenges in ME	Selected Interview Excerpts
Lack of operational context	• "Getting engineers to have the mission of ME. Some people work at a system for a long time but do not see the whole." • "I believe that most people are systems thinker. It's just their boundary is not as large as the bigger system. I don't believe that there are enough people who understand the broader context."

Critical Technical Implementation Challenges in ME	Selected Interview Excerpts
Requirements management	• "Mission engineering will have a lot to learn about getting it to meet the requirements." • "Finding documented fleet-level requirements is a challenge."
Complexity	• "In our organization, it is system of systems engineering (SoSE) – emerging behavior, independent behaviors – have all of it. They are also chaotic systems that are mixed with traditional systems. ME has to take it all into consideration where else systems engineering doesn't." • "The biggest problem is the complexity of the SoS." • "Use SE across all the domains and get them to translate across domains. The level of complexity gets exponentially challenging."
Testing & evaluation	• "Testing is hard in mission engineering. Each program and their detailed test plans look at their individual performance requirements. When you go to mission requirements, it's not the responsibility of one, but the collection of the program. Meet individual requirements but there's a mission shortfall... No one is doing mission testing." • "Test towards mission requirements. When you do mission engineering, it is critical to have program offices participate in solutions developments."
Analysis	• "Mission analysis is more precise when dealing with mathematical model. SE deals with more accurate model. If you have a systems engineer doing a mission architect, it would be better." • "There is a lack of understanding that this hasn't been done before. They do analysis on threats and kill chains but at the platform level, not the mission kill chain to be the most effective the organization can be."
Integration & Interoperability	• "One more challenge that is a concern is rooted in SoS. Extreme ties in SoS and ME. The ability to get the right data at the right time at the right place." • "Make ME integrated in their work. They're not used to it. Everyone should be a mission engineer. That would be part of the general work process."

Critical Technical Implementation Challenges in ME	Selected Interview Excerpts
Architecture	• "In SE we talk about physical architecture and functional architecture. But understanding the commercial architecture is also important. If I don't understand how the contracts and company incentives are structured, I can't do end-to-end service design. For a lot of physical systems we bought, I got the relevant agreement in place, but could have done better if we understood how important the commercial architecture was." • "Architecture design is essential from that perspective. Without a proper architecture, you won't understand the system."
Planning	• "We are initiating efforts to plan future capabilities and close gaps at the mission domain level in the organization. The organization and oversight to make this shift happen is in progress." • "Engineering parameter with constraints and schedule on how to perform the mission and stay within the cost – prediction and stay within the cost – it's something we struggle with."

3: MISSION ENGINEERING COMPETENCY

Based on the data collected (Appendices C-E), the RT-171 team developed a competency framework, which reflects the critical knowledge, skills, abilities, behaviors, and cognitions (KSABCs) for mission engineering. This was developed with three main efforts:

- The literature review provided an understanding of the critical activities of mission engineering, which provided insight into the skills required to perform those skills.

- The interviews provided detailed insights into the KSABCs that practicing mission engineers believe are critical to their work and that have been critical to their own success.

- The team reviewed multiple existing systems engineering competency models to identify common and consistent ways to define some of the overlapping competencies.

3.1 MISSION ENGINEERING COMPETENCY FRAMEWORK

The details of how the competency model was developed can be found in **Appendix C: Methodology**.

Figure 14 provides an overview of the competency framework developed by the RT-171 team for mission engineering. The framework was developed by developing critical competency groups from the data collected from both interviews and literature review (see Appendix D for additional detail). The framework, which is founded on the systems engineering competency framework presented in *Atlas 1.1* (Hutchison et al. 2018), is organized in the following ways:

- Competency **Areas** are groupings of related knowledge, skills, abilities, behaviors, and/or cognition.
  - Each Competency Area is comprised of **Categories**, which are specific types of knowledge, skills, abilities, behaviors, and cognition with shared characteristics.
    - Some categories are further refined into **Topics**, as defined by the qualitative data analysis (Appendix D).

Figure 14 includes the Areas and Categories of the Mission Engineering Competency Framework. There are six **Areas**:

1. *Discipline and Domain Foundations:* This area focuses on the foundational understanding of the systems that will be required to support a given mission.

2. *Mission Concept:* This area focuses on an individual's ability to understand and work within the context of a given mission, including understanding the overall concept, scenarios, and relevant mission threads as well as understanding the factors that may influence the mission in addition to technology (doctrine, processes, training, etc.).

3. *Systems Engineering Skills:* Mission Engineering and Systems Engineering share critical overlaps (see Section 1). This area provides clarity on the specific systems engineering KSABCs that are most critical for mission engineering.

4. *Systems Mindset*: This area is analogous with the systems mindset in *Helix* (Hutchison et al. 2018) and includes the cognitive abilities around thinking holistically as well as being able to identify the right levels of detail and integrate these perspectives.

5. *Interpersonal Skills*: This area includes the skills and behaviors associated with the ability to work effectively in a multi-team environment and to coordinate across the mission scope.

6. *Technical leadership*: Skills and behaviors associated with the ability to guide a diverse team of experts toward a specific technical goal.

1. Discipline & Domain Foundations

Principle and Relevant Disciplines
Relevant Domains
System Characteristics
Relevant Systems
Relevant Technologies
Acquisition Context

2. Mission Concept

Operational Context
Mission Concept of Operation
Mission Scenarios/Threads
DOTMLPF Space

6. Technical Leadership

Guiding Diverse Stakeholders
Team Building
Political Savvy
Decision Making
Workforce Development

5. Interpersonal Skills

Communication
Translation
Enterprise Context
Building & Utilizing a SME Network
Coordination
Influence, Persuasion, & Negotiation

3. Systems Engineering Skills

System of Systems Engineering
Analysis
Architecture
Modeling and Simulation
Requirements
Integration
Gap Analysis

4. Systems Mindset

'Big Picture' Thinking
Adaptability
Paradoxical Mindset
Multi-Scale Abstraction
Critical Thinking

Figure 14. Mission Engineering Competency Framework

Each of these **Areas** is elaborated in the sections below. The order listed above does not reflect priority or importance – all **Areas** are important for mission engineering – but rather helps to group similar items together and the second **Area** general builds upon the previous. Viewing from the top in clockwise order, consider the following clusters:

- **What** – **Areas** 1 and 2 are focused on the what – what is the mission? What is being developed? What disciplines support this? What are the characteristics of the mission? Individuals with competencies in these **Areas** would be able to answer these types of questions. The *Discipline & Domain Foundations* provide the crucial engineering and acquisition context, while the *Mission Concept* builds on this knowledge to define the expectations and critical operational context for the mission.

- **How** – **Areas** 3 and 4 are focused on how mission engineering is performed, with a focus on critical skills that enable individuals to perform mission engineering. The *Systems Engineering Skills* provide the engineering ability to do mission engineering while the *Systems Mindset* enables individual to apply the systems skills in the broader mission context.

- **Who** – **Areas** 5 and 6 are focused on the critical skills to enabling the teams that will deliver mission capabilities. *Interpersonal Skills* are critical for working in and across engineering teams while *Technical Leadership* skills are critical for leading and integrating across the many teams engaged in building the systems that generate a mission capability.

Note that foundational skills – e.g. math, natural or social sciences, general engineering skills - are not listed in the above. For all of the individuals interviewed for RT-171, a fundamental grounding in these areas was assumed. In terms of career paths, most stated that they had been systems engineers prior to becoming mission engineers, so this was considered an assumed skillset among mission engineers. And, because mission engineers do not frequently function as engineers at a system level, they must have sufficient skill to understand the work in these areas, but are not required to perform this work themselves.

3.1.1 AREA 1: DISCIPLINE AND DOMAIN FOUNDATIONS

Any given mission will cross multiple domains and require the support and integration of many engineering disciplines to be realized. Because basic understanding of math, sciences, and the fundamentals of engineering are assumed, the foundational building block for mission engineering, then, is an individual's abilities in the critical disciplines, domains, and technologies for a given mission as well as a grasp of complexity and the acquisition context in which they operate. This **Area** provides a grounding in the critical *systems* that will enable a mission.

1.1. **Principle and Relevant Disciplines:** *Disciplines* are fundamental areas of education or expertise that are foundational to a system. For example, for a communications system, electrical engineering will be an important discipline to understand, while civil engineering will be less relevant. Specialties are disciplines that support mission engineering by applying cross-cutting knowledge. Specialties include Reliability, Availability, and Maintainability (RAM), Human Systems Integration, Safety Engineering, Affordability and other related topics. A mission engineer needs to understand which of these disciplines are most critical to support a given mission.

1.2. **Relevant Domains:** *Domain* refers to the overarching area of application for a

given system; this includes things such as space, aerospace, marine, communication, finance, etc. Competency in relevant domains may enable an individual to be more effective.

1.3.　　**System Characteristics:** For mission systems, several specific charactersics were listed as critical and prevalent for mission systems. The most commonly-cited critical characteristics are provided below. However, when using this framework, the characteristics should be tailored to reflect the characteristics of the mission system.

a. **Complexity:** While systems will have a variety of characteristics that mission engineers must handle, for mission engineers, complexity is critical. In general, an individual will work on a spectrum of complexity, ranging from simple to complicated to complex to chaotic. (Adapted from the Cynefin framework, Snowden and Boone 2007) Complexity is generally note measured by the number of parts of a system – which would be a measure of how complicated a system is – but of the interactions between system elements, disciplines, or technologies, and the properties that emerge out of these interactions that are not present in the individual elements. Mission engineering involves multiple systems and/or systems of systems, each with their own inherent complexity and, therefore, mission engineers consistently work in the "complex" space. One categorization of complexity includes structural complexity, dynamic complexity, and socio-political complexity (Collins et al. 2017); while another identifies two kinds of complexity: disorganized complexity and organized complexity (SEBoK authors, "Complexity", 2016). For mission engineering, this includes not the complexities of an individual system, but of the interactions between multiple systems or systems of systems that will enable a given mission. In many ways, complexity is increased by the following three characteristics.

b. **Uncertainty:** Uncertainty is the result of not having accurate or sufficient knowledge of a situation. (ISO/IEC 2009) Because mission engineers are trying to integrate across a variety of systems or SoS's, it is not possible for them to have every detail on each mission system. Because mission engineers also may be from outside the organizations or even services where a system is being developed, it may also be difficult to obtain required information. Being able to function, and make decisions under uncertainty is a critical skill for mission engineers.

c. **Asynchrony:** As with many SoS's, mission systems have to deal with issues of asynchrony: the quality or state of being out of concurrence in time. When individual systems are acquired, they each have their own lifecycle. When these systems then need to be combined into a larger SoS to support a mission, their acquisition lifecycles may not change. As one interviewee stated, "But the challenge is all the bits are delivered asynchronously. If [a contractor] delivers a new system, they select technology that will be mature at CDR and then deal with obsolescence once the system is in service. In that scenario, I wouldn't expect my subsystems to change that often. But in mission engineering, you

have to expect that different bits will be delivered at different times. Some [are] nearly obsolete, some very new and untested." To be successful, mission engineers must be able to navigate asynchronous systems.

d. **Legacy Systems:** Though this is not unique to mission systems, especially in a defense context is it critical to understand what many legacy systems may be expected to integrate into the broader mission. One interviewee stated, "[We] do leap in technology but [we are also] dealing with systems that entered the fleet in 1952 or 1953 - need to account for these." Another interviewee provided a specific example of this, "For example, aircrafts like the B-52 have been on the 'on and off' status for ongoing efforts. Due to funding cost or program office service, it shifted into monitoring and weren't active – more for knowledge management." Mission engineers have to be able to deal with these issues.

1.4. **Relevant Systems in the Mission Space**: The two categories above define the systems in the mission space and how they are expected to interact. This category, however, is focused on the mission engineer's understanding of these critical systems. This is not to say that mission engineers must be experts in every system, but they should understand the context of each system, including the mission and organizational context in which it is being developed. This familiarity will better enable the mission engineer to anticipate potential problems when integrating systems to perform a specific mission.

1.5. **Relevant Technologies:** Within the context of a mission, there are specific technologies that are relevant. For example, on a marine system, these may be technologies such as gas turbine, radar, and sonar systems; and each technology has its own terminology, challenges, etc. A mission engineer must be aware of the most critical technologies for the systems that are included within a given mission.

1.6. **Acquisition Context:** The ways that systems are developed and acquired provides critical context and boundaries for the ways in which missions can be addressed. Particularly, government acquisition systems have standard processes and rules that constrain the ways in which mission engineers can impact the systems of systems that must integrate to achieve a mission goal. Without understanding the constraints of the acquisition system, a mission engineer can not effectively enable a given mission. This includes understanding the acquisition context of the programs that support the mission and where each of these programs fits within the acquisition process. This asynchronicity contributes to the complexity of mission engineering.

It is important to note that this skillset around working in an acquisition environment must also be paired with understanding the mission environment (described in Section 3.1.2 below). One of the challenges in mission engineering is the dichotomy between the acquisition view of systems and the mission view of systems of systems (described in Section 2 above). It is mission engineers with both skillsets that were reported to be move effective.

3.1.2 AREA 2: Mission Concept

The first **Area**, above, provides the foundations for a mission engineer to be able to understand the systems which make up a mission. This **Area** defines the skills required for the mission engineer to understand the mission itself and how constituent systems are expected to support and enable the mission.

2.1. **Operational Context:** The operational context is the combination of the conditions, circumstances, and influences which will determine which systems will be used. In a Defense context, this includes the use of military forces. One of the most consistent themes heard throughout the interviews was the criticality of being able to understand all the systems that support a mission not just theoretically, but also in terms of how they function and the environment(s) in which they are expected to function. Several interviewees stated that they hired individuals with operational expertise such as Navy Seals or Army Special Forces. Their operational understanding is critical to successful mission engineering. These individuals often did not have a background in mission engineering, so their organizations trained them in mission engineering or paired them with experienced mission engineers.

2.2. **Mission Concept of Operations**: A system concept of operations (ConOps) is a lens through which to view a system, specifically of how key users will interact with the key systems within a mission. A *mission* ConOps is the view of the critical systems required to complete a mission which highlights how these systems will interact at a high-level to produce the desired mission effects.

2.3. **Mission Scenarios/Threads**: Related to the Mission ConOps, mission threads define the end-to-end execution of a mission and enable individuals to understand how all the systems of systems work together. However, as opposed to the mission ConOps, which is intentionally at a high level, *mission threads include multiple levels of abstraction and are designed to enable each team working on a system or system of systems in the mission space to understand how to integrate with and support the overall mission.* This should help engineering teams understand the critical mission constraints of their systems and incorporate these constraints into their designs.

2.4. **DOTMLPF Space:** A critical aspect of mission engineering is understanding not only the systems required but also any areas where non-technical changes must be made to enable a mission. Many participants cited the DOTMLPF (Doctrine, Operations, Training, Materiel, Logistics, Personnel, Facility) considerations as a critical piece of the mission engineer's toolkit. Specifically, when working within the constraints of the acquisition system, where mission engineers may influence but not control systems, understanding when a mission need can be met with non-technical solutions or where an existing policy or practice must change in order to meet that need, is critical to successfully implementing mission approaches.

3.1.3 AREA 3: SYSTEMS ENGINEERING SKILLS

As described in Section 1, there are critical overlaps between mission engineering and systems engineering. To that end, participants described which systems engineering skills are particularly critical for mission engineers, which are reflected in this **Area**.

3.1. **System of Systems Engineering:** Missions require a complex set of systems to work together to achieve a task that, likely, many of these systems were not designed to do. This is a classic system of systems problem. Maier (1998) defines a system of systems as an assemblage of components which individually may be regarded as systems, and which possess two additional properties: (a) operational independence of the components, so that if a system-of-systems is disassembled into its component systems, the component systems must be able to usefully operate independently, and (b) managerial independence of the components meaning the component systems not only *can* operate independently, they *do* operate independently. (p. 267-284) As stated throughout the research interviews, system of systems engineering is highly synonymous with mission engineering. Therefore, mastery of system of systems principles is critical for mission engineers to be effective.

3.2. **Analysis:** While synthesis – understanding how systems of systems can combine to deliver an overarching mission – is important and reflected above, another critical skill for mission engineers is that of analysis. Analysis is the use of data, simulations and theory to understand how something works, which may require breaking problems or systems down into smaller parts.

3.3. **Architecture:** Mission engineers consistently stated in their interviews that architecting was a critical skillset for mission engineers. Being able to develop architecture at the mission level is necessary to enable the diverse set of engineering teams to understand their role in the broader mission context. Likewise, an understanding of architecture is important; mission engineers must be able to understand the high-level architecture of the systems of systems with which they interact and how these architectures may or may not be compatible with the desired mission architecture.

3.4. **Modeling and Simulation:** Today, most individual systems are sufficiently complicated and complex that no one person can understand the entire system holistically. Complexity increases exponentially as individual systems come together to complete a goal as a system of systems. For most missions, multiple systems of systems may be required to produce the desired mission effect. Clearly, no human being can fully understand and control this level of complexity. This is why modeling is a critical supporting discipline for mission engineering. Models allow appropriate simplifications to be made so that a human being can grasp the big picture of a mission. Rigorous models can also enable mission engineers to make trade-offs between the systems of multiple programs. Effective models can also be used as communication tools to enable a clear mission vision across the various systems and systems of systems involved.

3.5. **Requirements:** Finally, requirements engineering is a critical skill for mission

engineers. One of the biggest challenges mission engineers cited in their interviews was the fact that current mission-level requirements are seldom generated and, when they are, they are often generated after many of the critical systems and systems of systems are already under development. The ability to clearly identify the most critical requirements for a mission and coordinate with the supporting systems and systems of systems to help them understand how to meet these mission level requirements is critical for mission engineering success.

3.6.   **Integration:** IEEE 12207 defines integration as "a process that combines system elements to form complete or partial system configurations in order to create a product specified in the system requirements." (ISO/IEEE 2008) In the context of mission engineering the concept expands to include combining not just system elements but entire systems or systems of systems with operational context and processes and proceedures to help bring a mission together. Because missions tend to include many disparate systems or SoS's, the ability to understand how the pieces can and must fit together to enable a mission is critical.

3.7.   **Gap Analysis:** Gap analysis is traditionally the comparison of actual performance with potential or desired performance. This definition applies in a mission context, but gap analysis for mission engineering can also include the comparison of planned performance for an individual system versus the planned performance for that system in a mission context. A key example of this in a SoS is that of the Joint Tactical Radio System (JTRS) and the Army's Future Combat System (FCS). JTRS was intended to provide the critical communications infrastructure for FCS. There were many complications in the integration between JTRS and FCS. However, as noted in a CFS report, "The inability to meet … fundamental design and performance standards raised concerns that [JTRS] may not be able to accommodate," some of the critical uses for FCS. (CRS 2005) A comparison of what JTRS was required to provide – requirements that were set in the mid-1990s – and where its capabilities were actually evolving, was a critical activity for FCS engineers.

There are many other systems engineering KSABCs that could support mission engineering. However, for this report, the critical skills that were consistently cited by interviewees are the ones highlighted here. As described in Section 3.1, the competency framework is expected to be tailored and additional systems engineering skills could certainly be added as part of this tailoring.

3.1.4 AREA 4: SYSTEMS MINDSET

Systems Mindset is primarily focused on patterns of thinking, perceiving, and approaching a task that are particularly relevant to mission engineers, including holism and integration. The categories included in this area are:

4.1.   **Big-Picture Thinking**: Also referred to as 'systems thinking' and 'holistic thinking', this includes the ability to step back and take a broader view of the problem at hand;

this is an important and essential characteristic of mission engineers. 'Big-picture' could refer to a broader perspective along many different dimensions: the system as a whole including interfaces and integration, and not limited to any sub-system or component; the system while in operation, and its interactions with other systems and the operating environment; the entire lifecycle of the system, and not limited to the current stage of the system; the development program in the context of the organization and all its other development programs; the end goal or solution to the problem at hand; the perspectives of different stakeholders; and the technical as well as the human and business perspectives. A mission engineer is usually *the* person to bring this broader perspective, while classic engineers and subject matter experts often tend to be narrowly focused on their area of interest. Mission engineers are not only called to provide this big-picture perspective themselves, but also to enable others to see this bigger picture.

In addition to the broad category of "big picture" thinking, there are specific techniques and mindsets that are critical for thinking holistically about systems of systems. Keating and Gheorghe (2016) state that for systems of systems thinking, the focus is on system behaviors and specifically on the synergies created by interactions of specific systems, rather than from the specific systems themselves. Because missions require systems of systems working together, this focus on synergistic behavior is crucially important for mission engineers. This is not out of scope for general "systems thinking" but is important to highlight in a mission context.

4.2. **Adaptability**: *The overall ability to deal with ambiguity and uncertainty, this involves the abilities to be open-minded, understand multiple disciplines, deal with challenges, and the ability to take rational risks*. By definition, experts possess competency in a specific area, which is their 'comfort zone'; and they typically do not prefer going outside that circle or comfort zone. Such experts provide value to the organization by contributing their expertise in those focused areas. However, mission engineers tend to show an ability to broaden their comfort zones, and go beyond their current boundaries and they are also comfortable doing this.

4.3. **Paradoxical Mindset**: *The ability to hold and balance seemingly opposed views, and being able to move from one perspective to another appropriately*. Typically, an engineer may hold one view or the other, but rarely *both*. By having this paradoxical mindset, a mission engineer contributes value that is not usually expected from others. The opposing-concept pairs are:

4.2.1. Big-Picture Thinking *and* Attention to Detail: Big-picture thinking provides the broader higher-level perspective; at the same time, a mission engineer is also required to pay attention to the details of how things work and how they come together in a system.

4.2.2. Strategic *and* Operational: Mission engineers need to be strategic, focused on the end result of 'vision' for the mission, but also need to handle the tactical day-to-day activities and decisions required to reach that vision. They must also be able to appreciate "how what is done today is going to affect things

downstream". A related concept pair is the ability to envision long-term issues but at the same time, have the drive for closure with the current situation in order to move on.

4.2.3. Analytic *and* Synthetic: A big-picture perspective may be associated with the ability to be synthetic, and to be able to bring together and integrate different pieces of a puzzle. However, a mission engineer also needs to be analytic and to be able to break down the big picture into smaller pieces on which others can focus and work. To do this effectively, a mission engineer needs to be able to operate at multiple levels (e.g., system, system-of-systems, and mission) and multiple dimensions (e.g., various technical disciplines and stakeholder perspectives).

4.4. Multi-Scale Abstraction: *The ability to filter out and understand the critical bits of information at the right level and to make relevant inferences.* Even with that filtered information, mission engineers using their mission engineering skills need to know when to use or not use pieces of information. Such abstraction also enables mission engineers to connect and extract meaning from different streams of information; for example, to tie together information that subject matter experts of two different disciplines are providing.

4.5. Critical Thinking: Critical thinking is the intellectually disciplined process of actively and skillfully conceptualizing, applying, analyzing, synthesizing, and/or evaluating information gathered from, or generated by, observation, experience, reflection, reasoning, or communication, as a guide to belief and action. (Paul and Elder 2008)

3.1.5 AREA 5: INTERPERSONAL SKILLS

The fifth competency area is *Interpersonal Skills*. Mission engineers can not work by themselves; they must interact with a variety of teams to affect change at the mission level. A mission engineer is expected to be proficient in a number of interpersonal skills. The specific categories contained within this competency area are listed below:

5.1. Communication: Communication is critical for mission engineers since they interact with a variety of people, and this is a broad category covering a wide variety of related skills and abilities. Often they are an important link between individuals and groups, both internal and external to the organization – most importantly, the customers and end-users of the system being developed. Mission engineers need the ability to clearly express their thoughts and perspectives to establish a shared common understanding.

5.1.1. Audience: Mission engineers need to communicate with a variety of direct and indirect audiences: customers; subject matter experts; program managers; vice presidents; directors; specialty engineers; problem owners; technical teams;

contractors; decision makers; system testers; and others working on or with the project.

5.1.2. Content: The variety of content that mission engineers need to communicate can be broadly divided into three types, based on the audience they are communicating with:

1. **Technical**: Communications with disciplinary and specialty engineers and subject matter experts involve high technical content. But communications of technical issues to managers, end-users, and others who may not be interested in or who may be confused by all the technical detail, involves adequate abstraction of the technical content.

2. **Managerial**: Mission engineers often provide project status to managers and supervisors and cost-schedule constraints and expectations to technical personnel.

3. **Social**: Mission engineers need to maintain an amicable environment within a team and to interact with others in a courteous manner. Such interactions involve communications that are neither technical nor managerial in nature.

5.1.3. Mode: Communicating the intended content to the target audience is done through a number of different modes:

1. **Oral:** This takes various forms, depending on the audience and context. It could be one-on-one, or as part of a team, in person, or remotely.

2. **Presentation**: A special form of communications is the ability to stand in front of an audience and to deliver a presentation using appropriate aids. Further, during presentations, mission engineers tend to represent others who may not be in the room: they present customer needs and requirements to others in the absence of customers, and they present design decisions and system related issues to customers in the absence of designers.

3. **Writing and Documentation:** Written communication skills are equally critical for mission engineers; the scale, audience, and objective of the written artifact also matter. It could range from a short email to communicate status, to a detailed test plan, to internal documentation supporting a project decision, to design documents being submitted for review.

5.2.   Translation: Building on the skills described under *Communication*, mission engineers serve a critical role as translators. They must help engineers understand the operational and mission context, operators understand engineering constraints, leadership at all levels understand the constraints of these environments, and help ensure that all stakeholders understand the impacts of the acquisition systems constraints on the art of what is possible for a given mission. Many mission engineers

stated that this was one of the most critical benefits mission engineers provide.

5.3.   **Enterprise Context:** The enterprise context is important in any system effort. As mission engineers try to influence multiple programs and projects to align with relevant missions, they must also have an understanding of the power structures and processes – 'how work gets done' – in each of the associated organizations. Without this skill set, individuals will struggle to bring about critical changes or garner support from decisions makers to enable mission development. These skills are critical to enabling mission engineers to influence stakeholders throughout the mission space.

5.4.   **Building & Utilizing a Subject Matter Expert (SME) Network:** A mission engineer needs to be a 'people person', and build a social network of professional acquaintances. Such a network becomes a valuable resource for mission engineers to tap into, because they are not expected to know answers to all problems, but rather be able to find someone who has the expertise and ability to solve the problem.

5.5.   **Coordination:** In this context, coordination is the organization of the different elements of a complex body or activity so as to enable them to work together effectively. A mission engineer must bring together and bring to agreement a broad set of individuals or groups who help to resolve mission related issues. This is an enabler to the *Guiding Diverse Stakehodlers* competency in the next area. (Modified from the definition of "coordinator", Sheard 1996 and Hutchison et al. 2018.)

5.6.   **Influence, Persuasion, and Negotiation**: It is critical for every mission engineer to have the skills needed to make a point and to successfully obtain buy-in. In many situations, mission engineers contribute a perspective that is different from that of others: a focus on the overall mission and directly on the strategic Defense needs. In such situations, it requires influence, persuasion, and negotiating skills for mission engineers to enable others to see the bigger picture on which they need to focus. As described in Section 1, mission engineers are often not empowered with any authority to enact the changes required to move a system already in development to be aligned with a mission need. They must therefore be persuasive and try to influence programs over which they have no direct control or authority.

Conflicts are bound to rise in a variety of scenarios – across teams, organizations, and services – between the technical side and business side of the organization; as well as outside of the organization. The mission engineer must resolve these conflicts while keeping the system goals in mind. In some cases, conflicts arise due to the existence of barriers, which may be related to the organizational culture, processes, team personalities, or other situations that could prevent an individual or team from getting their work done. The mission engineer needs the ability to break these barriers.

3.1.6 AREA 6: TECHNICAL LEADERSHIP

The sixth and final competency area is *Technical Leadership*. It is common and natural for mission engineers to play leadership roles at many levels within an organization. The specific categories contained within *Technical Leadership* are listed below.

6.1.   **Guiding Diverse Stakeholders:** This includes the ability to manage all the internal and external stakeholders, and to keep all teams engaged in the mission focused on the variety of stakeholder needs, especially those of the end user or customer. The mission engineer is uniquely positioned to interact with many stakeholders of the system – both external and internal to the organization. Being this 'touch point' person, the mission engineer needs to deal with multiple personalities, behaviors, organizations, and cultures. A key activity in this area is helping to manage expectations on the mission needs versus the individual system needs.

6.2.   **Team Building:** *The ability to identify, build, and effectively guide or coach a team comprising individuals with diverse expertise, perspectives, and personalities.* A mission engineer is charged with coordinating across programs and projects to deliver a mission engineering capability. The mission engineer needs to fully know each of the team members: their strengths, weaknesses, capacities, capabilities, limitations, personalities, expertise, and working styles. The mission engineer plays the roles of coach, guide, and teacher to develop the team's capabilities and to orchestrate it to perform the required tasks. Individual leadership styles could vary, but the overall objective of is to empower the team, to instill confidence, and to help them to deliver the solution and to be successful. Another key aspect of handling a team is the ability to delegate – the leader needs to build enough trust in the team to be able to delegate with confidence.

6.3.   **Political Savvy:** Political awareness is the "ability to understand different people's agendas, and use this knowledge" to enable progress and influencing more effectively and with more sensitivity to different viewpoints. (Expert Program Management, 2018) Because mission engineers work with teams that span multiple organizations – across services, domains, and a combination of government and industry – understanding the political landscape is an important skill. This is a critical piece of context for the ability to *Guide Diverse Stakeholders* and provides critical understanding required for *Influence, Persuasion, and Negotiation*.

6.4.   **Decision Making:** Specifically, the skillset that enables individuals to make decisions, especially with a group of people and when limited information is available. Though decision making requires interpersonal skills, in a mission engineering context, it is also critical for building consensus building between multipole stakeholding, requiring leadership and influence skills. For example, mission engineers may need to help systems engineers and program managers accept the trade-offs for their systems in favor of the mission; i.e. perhaps suboptimizing an individual system to enable the system to support the mission.

6.5.   **Workforce Development:** Because mission engineering is an emerging discipline, one of the competencies that mission engineers are currently concerned with is how to build teams and develop individuals so that thye can perform in mission engineering. As the discipline matures, individual mission engineers may be less concerned with this, but at the present time, this is an important aspect of how mission engineers function.

3.2 TAILORING THE COMPETENCY FRAMEWORK

The ME Competency Framework provides the basis for creating a tailored version that can align with a specific mission. Individuals may tailor the framework specifically based on what they have done – but should be mindful that all of the areas they have not touched are possible areas for future exploration. Organizations, likewise, could tailor the framework before asking the workforce to perform their assessments, so that only areas that are deemed critical to the organization are captured. For example, relevant disciplines and domains will vary depending on mission and the specific missions required.

Table 9 provides two examples of how the competency framework could be tailored, based on two specific missions that are described in Section 1: the DoD's Intelligence, Surveillance, Reconnaissance (ISR) mission and the NASA Journey to Mars. Note that where <no tailoring> is listed, this indicates that the team expects that either an organization will be able to use the competency framework exactly as defined, with no tailoring required, or that for purposes of this example, no specific tailoring has been identified.

Table 9. Tailoring the Mission Engineering Competency Model

Area	Category	Mission 1: ISR	Mission 2: Journey to Mars
1. Discipline & Domain Foundations	**1.1.** Principle and Relevant Disciplines	EE, CS/CE, ME, IT	EE, ME, Aeronautical Eng, Physiology, Thermodynamics
	1.2. Relevant Domains	Telecom, IT,	Space, logistics and supply chain
	1.3. System Characteristics	Divining intentions of thinking opponents, i.e., high complexity	Pioneering approach to enable a sustained expansion of humans on Mars with uncertainties in funding and emergence of new technologies and scientific knowledge (NASA 2015)
	1.4. Relevant Systems	National Geospatial-Intelligence Agency (NGA) systems; Navy Distributed Common Ground/Surface System (DCGS); Marine Corps DCGS; Army DCGS; Air Force DCGS, Special Operations Forces DCGS, Intelligence Community (IC) DCGS	SLS, Orion, International Space Station, Commercial Orbital Transportation Services, Commercial Crew Transportation Capability
	1.5. Relevant Technologies	<no tailoring highlighted>	Space Launch System (SLS) and Orion crewed spacecraft
	1.6. Acquisition Context	Commercial technology refresh cycle vice legacy acquisition approach. i.e., faster!	Commercial services such as crew and cargo
2. Mission Concept	**2.1.** Operational Context	<no tailoring highlighted>	Expanding on the robotic legacy for human exploration on Mars through Earth Reliant exploration onboard the ISS to develop deep space

Area	Category	Mission 1: ISR	Mission 2: Journey to Mars
			systems, life support, and human health reseach to ensure the safety and protection of the human explorers
	2.2. Mission Concept of Operations	Familiarity with CONOPS for ISR across all services. joint commands, and intelligence community	Familiarity with CONOPS for manned journey to Mars
	2.3. Mission Scenarios/Threads	Joint intelligence preparation of the operational environment; Indications and warning; ISR mission management; Intelligence support to targeting; Battle damage assessment	Advance the Earth Reliant human spaceflight program through the Proving Ground of cislunar space to an Earth Independent, deep-space capability (NASA 2015)
	2.4. DOTMLPF Space	Per Defense Intelligence Informaton Enterprise (DI2E)	<no tailoring>
3. Systems Engineering Skills	**3.1.** System of Systems Engineering	Embracing and managing uncertainty	<no tailoring>
	3.2. Analysis		
	3.3. Architecture		
	3.4. Modeling and Simulation		
	3.5. Requirements Engineering		
	3.6. Integration		
	3.7. Gap Analysis		
4. Systems Mindset	**4.1.** Big-Picture Thinking	e.g., US Navy Commander Joe Rochefort and his communications intelligence (COMINT) team in Hawaii divining Japanese Navy intentions leading up to the Battle of Midway Pioneering space for sustained human exploration and expansion on Mars	Pioneering space for sustained human exploration and expansion on Mars
	4.2. Adaptability		Standardize for flexibility and simple interfaces to enhance complex subsystems
	4.3. Paradoxical Mindset		<no tailoring>
	4.4. Multi-Scale Abstraction		
	4.5. Critical Thinking		
5. Interpersonal Skills	**5.1.** Communication	e.g,, Commander Joe Rochefort and his COMINT team before the Battle of MIdway	Engaging all four NASA Mission Directorates and all NASA Center and Laboratories, as well as fostering new and existing international public and
	5.2. Translation		
	5.3. Enterprise Context		

Area	Category	Mission 1: ISR	Mission 2: Journey to Mars
	5.4. Building a and Utilizing a SME Network		private partnerships
	5.5. Coordination		
	5.6. Influence, Persuasion, and Negotiation		
6. Technical Leadership	**6.1.** Guiding Diverse Stakeholder		
	6.2. Team Building		
	6.3. Political Savvy		
	6.4. Decision Making		
	6.5. Workforce Development		

Table 9 is only a basic example, but demonstrates that tailoring can include the identification of specific competencies that are of critical interest to specific missions – particularly in Competency Areas 1 and 2, which are expected to be heavily tailored.

3.3 COMPETENCY ASSESSMENTS

In identifying how competencies might be assessed, the RT-171 team examined guidance from a number of sources, such as the *Atlas* model created by the Helix research project (Hutchison et al. 2018) and the draft INCOSE competency model (Gelosh et al. 2017). The INCOSE competency model attempts to create a detailed description of each 'proficiency level' (level of competency attainment) for each individual competency. The Helix model takes a different approach. As explained in (Hutchison et al. 2016):

> *One of the areas that has proven more difficult than expected for the Helix team is the development of a rubric to guide assessment of proficiencies. The team has helped over 100 individuals conduct self-assessments and had exploratory conversation around these assessments, but the primary roadblock to this has been that individuals struggle to explain skills versus how they attained them. For example, if an individual said that they were a 6 out of 10 for "Systems Engineering Discipline", the team would ask what that "6" really meant. The answers would often be something like this: Well, I've been doing systems engineering for 5 years and I've seen most of the lifecycle and I am good with the tools we utilize here." Note that "I've seen most of the lifecycle" – an aspect of their career path – is different from "I am able to provide clear value and*

leadership at any stage of the lifecycle." When the team probed further, individuals simply did not have the vocabulary to describe precisely the differences between a "5 out of 10" and a "7 out of 10".

In their work to be published in 2018, Pyster, Hutchison, and Henry tackled this in a different way. They identified a comparable competency scale which is somewhat generic – utilizing broad descriptions for a level of competency – rather than trying to tailor a specific definition for every single topic. This is adapted from a rubric developed by the National Institutes of Health (NIH), the "NIH Competency Scale is an instrument used to measure one's ability to demonstrate a competency on the job. The scale captures a wide range of ability levels and organizes them into five steps; from 'Fundamental Awareness' to "Expert'." Pyster et al. have adapted this to apply to the *Atlas* framework, translating the levels into a 5-point scale (1 for Fundamental Awareness, 2 for Novice, etc.). (2018, in print) This is illustrated in Table 10 and the RT-171 team recommends that this is a useful approach for beginning competency assessment for mission engineers.

Table 10. Competency Levels (adapted from Pyster et al. 2018, in print, used with permission)

#	Level	Level Description
1	FUNDAMENTAL AWARENESS	Individual has common knowledge or an understanding of basic techniques and concepts. Focus is on learning rather than doing.
2	NOVICE	Individual has the level of experience gained in a classroom or as a trainee on-the-job. Individual can discuss terminology, concepts, principles, and issues related to this competency, and use the full range of reference and resource materials in this competency. Individual routinely need help performing tasks that rely on this competency.
3	INTERMEDIATE	Individual can successfully complete tasks relying on this competency. Help from an expert may be required from time to time, but the task is usually performed independently. The individual has applied this competency to situations occasionally while needing minimal guidance to perform it successfully. Individual understands and can discuss the application and implications of changes in tasks relying on the competency.
4	ADVANCED	Individual can perform the actions associated with this competency without assistance. The individual has consistently provided practical and relevant ideas and perspectives on ways to improve the competency and its application and can coach others on this competency by translating complex nuances related to it into easy to understand terms. Individual participates in senior level discussions regarding this competency and assists in the development of reference and resource materials in this competency.

#	Level	Level Description
5	*EXPERT*	Individual is known as an expert in this competency and provides guidance and troubleshooting and answers questions related to this competency and the roles where the competency is used. Focus is strategic. Individual have demonstrated consistent excellence in applying this competency across multiple projects and/or organizations. Individual can explain this competency to others in a commanding fashion, both inside and outside their organization.

Mission engineers can use this guidance in Table 10 to complete their own assessments. In a related SERC project – RT-173: Helix – these types of self-assessments have been conducted for systems engineers. The Helix team recommends that proficiencies could be reviewed at two points in time: (1) present day, and (2) a point in the past, often at the start of one's career. This enables a competency profiles to be plotted, as illustrated in Figure 15. (Hutchison et al. 2018)
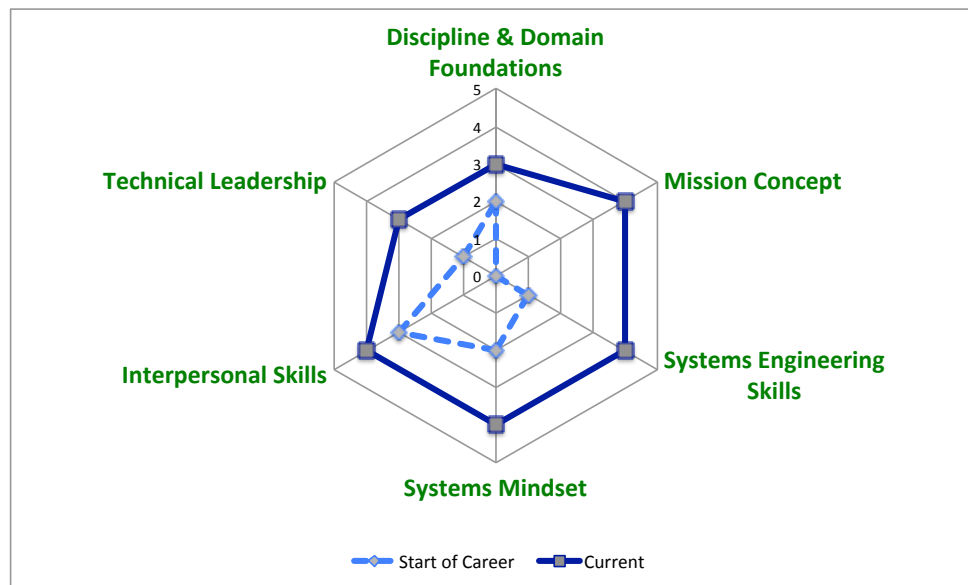
Figure 15. Example Competency Profile for an Individual

The competency profile is not meant to be exact since self-evaluations are subjective, and individuals may have over- or under-rated themselves. However, this exercise enables a discussion around the relative strengths in specific competencies; how competency levels changed over time; and what factors or forces caused or enabled those changes.

This framework can also be used to support the development of future mission engineers who will be effective. From a competency perspective, it would mean setting target levels for competency areas, as illustrated in Figure 16.
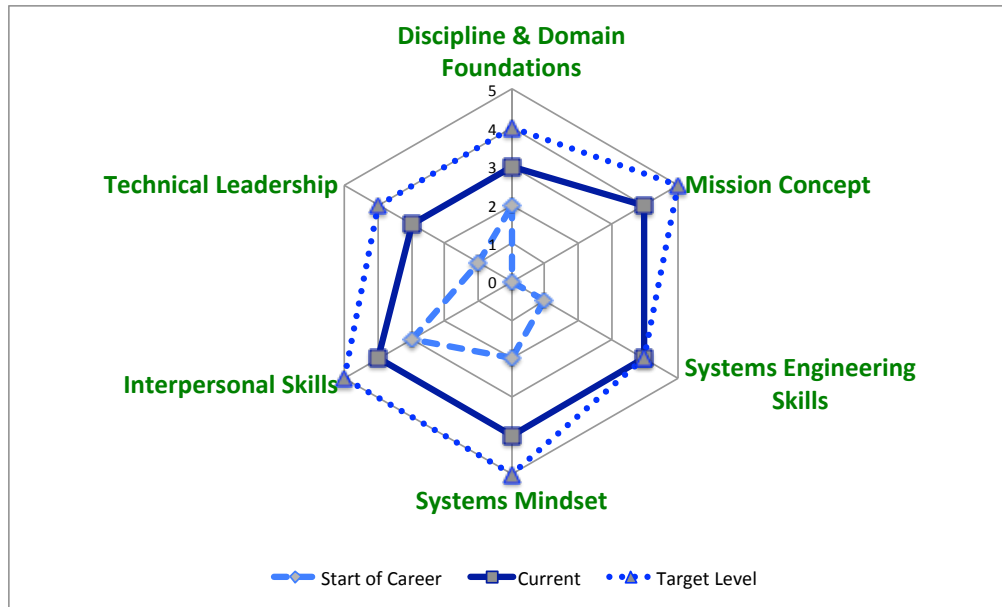
Figure 16. Example Competency Profile with Target Levels

3.4 MISSION ENGINEERING TEAMS

The competency framework includes all of the competencies that are required to make mission engineering work. However, it is important to note that mission engineers often work in teams – sometimes with other mission engineers but always with groups of project managers, systems engineers, discipline engineers, etc. Therefore, it would be unwise and unrealistic to treat the competency as something that each individual mission engineer must attain to the highest level.

In the related Helix research, employees found organizational expectations for "superhero" profiles. Their rationale was that if the organization truly expected them to be expert in everything, then there was no way they would be able to fulfill those expectations. These unrealistic expectations can make systems engineers – or mission engineers – believe that their contributions could not be valued by their organization. (Hutchison et al. 2018b)

In some organizations from the Helix research, discussions about expectations led to the realization that the "minimum" was what was needed from a team of individuals, not teams. Thinking holistically about the capabilities required from a team helps to alleviate the problem of expecting individuals to have the highest proficiency in every competency (which is, as stated above, nearly impossible). Figure 17 shows an example of this:
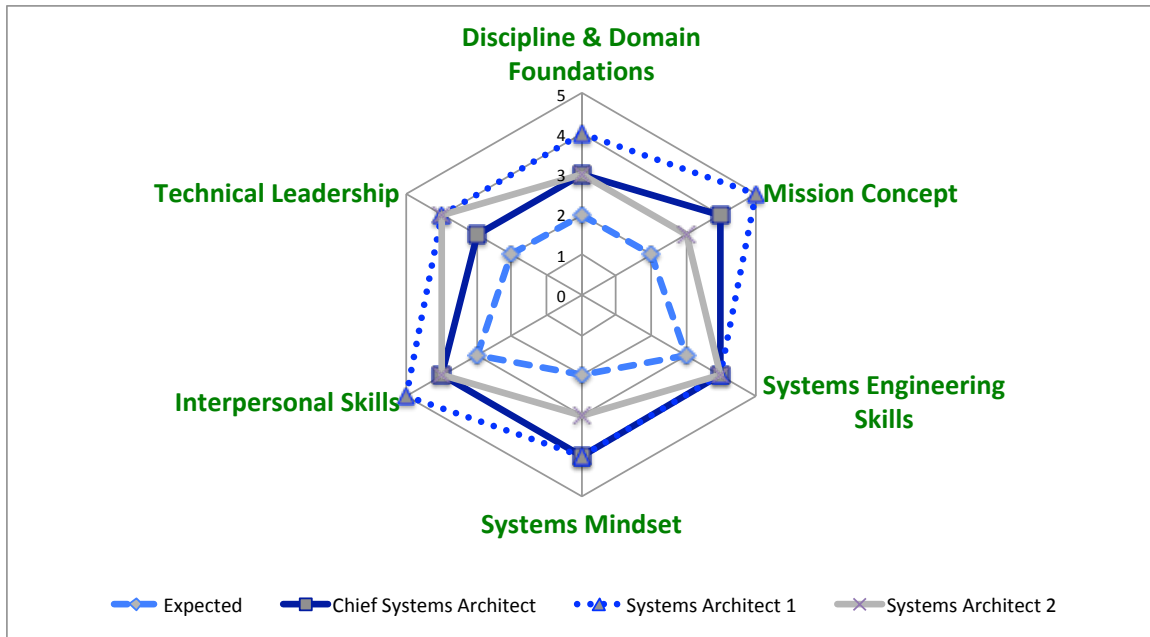
Figure 17. Example of team profiles compared to an "expected" profile.

In the figure above, it looks as if the team would fall short of expectations in half of the critical proficiency areas. However, team personalities and dynamics will also influence this picture. It is possible that if the team works well together, they will create synergies that enable them collectively to be more effective than they could be individually. Again from the Helix research, there were several real-world examples of teams where no single individual met all expectations, but as a team, the team fulfilled all expectations.

This type of approach for understanding competencies is important in mission engineering as well. In particular, how mission engineers can integrate into and influence the various teams working on systems within the mission space will be critical for understanding how they might be effective.

3.5 COMPARISON TO RELATED COMPETENCY MODELS

The intention here is to highlight where the findings from RT-171 are consistent with or differ from existing competency models. If we are not going to include an actual competency model, suggest we still compare findings with: INCOSE SE Competency model, NASA SE Competency Model, and the Helix SE proficiency model.

3.5.1 MISSION ENGINEERING COMPETENCY AND THE HELIX (*ATLAS*) SE PROFICIENCY MODEL

The formatting and approach for the Mission Engineering competency framework is based upon the Helix (*Atlas*) systems engineering proficiency model. For this reason, it is a useful model to begin comparisons.

The Helix model focuses on 6 proficiency areas (Hutchison et al. 2018):

1. ***Math/Science/General Engineering:*** Foundational concepts from mathematics, physical sciences, and general engineering;

2. ***System's Domain & Operational Context****: Relevant domains, disciplines, and technologies for a given system and its operation;

3. ***Systems Engineering Discipline***: Foundation of systems science and systems engineering knowledge;

4. ***Systems Mindset***: Skills, behaviors, and cognition associated with being a systems engineer;

5. ***Interpersonal Skills***: Skills and behaviors associated with the ability to work effectively in a team environment and to coordinate across the problem domain and solution domain; and

6. ***Technical Leadership***: Skills and behaviors associated with the ability to guide a diverse team of experts toward a specific technical goal.

Immediately there are several common areas – though the categories included in these areas are not identical. Systems mindset was consistently cited as critical for mission engineers, as were interpersonal skills, and technical leadership. Table 11 provides a detailed cross-walk between the ME Comptency Framework and the *Atlas* systems engineering competency model.

Table 11. Comparison of Mission Engineering Competency Framework and Helix (*Atlas*) Proficiency Model

ME Area	SE Area (*Atlas*)	Discussion
Discipline and Domain Foundations 1.1. Principle & Relevant Disciplines 1.2. Relevant Domains 1.3. Relevant Technologies 1.4. Complexity 1.5. Acquisition Context	**Math/Science/ General Engineering** 1.1. Natural Science Foundations 1.2. Engineering Fundamentals 1.3. Probability and Statistics 1.4. Calculus and Analytical Geometry 1.5. Computing Fundamentals	For both models, these are the foundational skills on which the discipline is based. Virtually no one in the ME competency study talked about general math, science, or engineering skills – they were assumed as a baseline – whereas in *Atlas*, systems engineers discussed this explicitly as the foundation for their discipline. For ME, the foundations were considered the knowledge of the critical domains, disciplines, and technologies that support those disciplines. Similarly to *Atlas*, the consensus for ME was not that a mission engineer must be an expert in each of these, but instead that a mission engineer must have "enough depth" in these to knowledgably engage with SMEs.
Mission Concept 2.1. Mission Concept of Operations 2.2. Mission Scenarios/Threads 2.3. Relevant Systems in the Mission Space	**Systems Domain and Operational Context** 2.1. Principal and Relevant Systems 2.2. Familiarity with Principal System's Concept of Operations (ConOps)	Critical to mission engineering is a clear grasp on the mission itself – what is the goal, how will it be achieved, and the critical system(s) relevant to the mission, looking not only at technology but other factors that will impact mission success, such as logistics, personnel, and processes. This is analogous to the *Atlas* Systems Domain and Operational Context. Really, these are different lenses through which to view a system: for *Atlas* it is on the

ME Area	SE Area (*Atlas*)	Discussion
2.4. DOTMLPF Space	2.3. Relevant Domains 2.4. Relevant Technologies 2.5. Relevant Disciplines and Specialties 2.6. System Characteristics	specific system being developed in context while for mission engineering it's the context for the system of systems that can deliver a capability.
Systems Engineering Skills 3.1. System of Systems Engineering 3.2. Architecture 3.3. Modeling 3.4. Analysis 3.5. Requirements Engineering	**Systems Engineering Discipline** 3.1. Lifecycle 3.2. Systems Engineering Management 3.3. SE Methods, Processes, and Tools 3.4. Systems Engineering Trends	For ME and *Atlas,* this area talks about the importance of the discipline of systems engineering. . As many defined mission engineering as strongly related to systems engineering (see Section 2), it is unsurprising that there is clear overlap. In *Atlas*, this is a well-rounded view across the entire discipline. For mission engineering, however, there were specific facets of ME that were repeatedly highlighted: architecture, requirements, modeling and simulation, analysis, and again, the broader lens of system of systems engineering. All of these are lower-level topics in the *Atlas* model but based on the interview data, rise to the importance of specific critical categories for ME.
Systems Mindset 4.1. Big-Picture Thinking 4.2. Paradoxical Mindset 4.3. System of Systems Thinking 4.4. Adaptability 4.5. Multi-Scale Abstraction	**Systems Mindset** 4.1. Big-Picture Thinking 4.2. Paradoxical Mindset 4.3. Adaptability 4.4. Abstraction 4.5. Foresight and Vision	Here, there is a strong correlation between the ME framework and *Atlas* model. As many defined mission engineering as strongly related to systems engineering (see Section 2), it is unsurprising that the thought patterns and approaches that support systems engineering were also viewed as crucial for mission engineering. The major difference here was, again, how critical the interviewee's believed the SoS perspective is for mission engineers. This is not to say that big picture thinking can not include a SoS perspective for systems engineers – just that for mission engineers it was seen as consistently critical. One of the other differences is that "foresight and vision" were not described in the same way for ME as for *Atlas*. Specifically, mission engineers often described dealing with emergence and unpredictability successfully – the adaptability – over the ability to predict how things would work in these complex SoS's.
Interpersonal Skills 5.1. Communication 5.2. Translation 5.3. Influence, Persuasion, and	**Interpersonal Skills** 5.1. Communication 5.2. Listening and Comprehension 5.3. Working in a Team	Both mission and systems engineers require strong interpersonal skills to be successful. The most commonly-cited for both ME and *Atlas* was "communication" – though in *Atlas* listening and comprehension were critically highlighted whereas in ME, translation – the ability to help multiple stakeholders understand the views of other stakeholders

ME Area	SE Area (*Atlas*)	Discussion
Negotiation 5.4. Building a Social Network 5.5. Enterprise Context	5.4. Influence, Persuasion, and Negotiation 5.5. Building a Social Network	by "translating" concerns across organizational and disciplinary boundaries – was very commonly cited as critical. For *Atlas*, functioning in team was consistently highlighted. However, in ME, it is generally a very small team of 2-3 mission engineers who instead are more focused on interfacing with the engineering teams across a number of projects and programs. Often they are outside of these programs, and therefore rather than integrating into a team must focus on influencing these programs or projects. Systems engineers also need to influence – as organizationally they often do not control other engineers – but this skill is required at a different level for mission engineers. Both mission and systems engineers require the ability to build and utilize a network of subject matter experts that can provide critical technical insights. For mission engineers, this network also commonly included operators with in-depth knowledge of many of the systems that support a mission in practice. Finally, while systems engineers did occasionally cite understanding how their organizations work as important, it did not rise to the level of a proficiency category. In contrast, mission engineers cited how critical it is to understand not only their own organizations but all of the organizations that interact with the mission system, including understanding multiple command and control chains and even sometimes across services. Having this context of the broader enterprise was cited as critical for successful mission engineering.

ME Area	SE Area (*Atlas*)	Discussion
Technical Leadership 6.1. Guiding Diverse Stakeholder 6.2. Team Building 6.3. Political Savvy 6.4. Decision Making 6.5. Workforce Development	**Technical Leadership** 6.1. Building and Orchestrating a Diverse Team 6.2. Balanced Decision Making & Rational Risk Taking 6.3. Guiding Diverse Stakeholders 6.4. Conflict Resolution & Barrier Breaking 6.5. Business and Project Management Skills 6.6. Establishing Technical Strategies 6.7. Enabling Broad Portfolio-Level Outcomes	While guiding diverse stakeholders was important for systems engineers, it was the most commonly cited technical leadership skill for mission engineers. In both approaches team building was critically important. However, for mission engineering – which crosses organizational and sometimes enterprise boundaries – political savvy was seen as critically important. Again, this does not mean that it is unimportant for systems engineering but that it was a strong tend for mission engineering and was not commonly cited in the Helix study. Because mission engineering is an emerging discipline, workforce development and mission engineers' critical role in growing additional mission engineers was commonly cited. While workforce issues were also cited in *Atlas*, the ability to grow systems engineers did not emerge as a critical competency.

3.5.2 MISSION ENGINEERING COMPETENCY COMPARED TO ADDITIONAL COMPETENCY MODELS

Because the shape of the ME Comopetency Framework was influenced by *Atlas*, it was possible to do a clear mapping between the competency areas. This is not, however, feasible when comparing to other competency models. Instead, the team provides the comparison in Figure 18 illustrates the overlap between the ME Competency Framework and additional related frameworks: the INCOSE SE Competency Framework (2018 in print), the NASA SE Competencies (2017), and the Navy SE Competency Model (Whitcom et al. 2015). Competencies from the INCOSE model are listed in blue; competencies from the NASA model are listed in green; competencies from the Navy SE competency model are in navy blue.

Comparing the ME Competency Framework to other models served several purposes:

- It enabled the team to identify whether there were related competencies that were excluded from the ME Competency Framework and, if deemed critical, to examine the reason for the omission. For example, did the team prompt for this response in the questions?

- It enabled the team to identify competencies that were unique to the ME Competency framework, which helps to highlight how mission engineering differs from related disciplines like systems engineering.

- Overlaps helped to identify key areas where mission engineering is related to other disciplines.

Technical Leadership/Leadership

Team Dynamics/Team Dynamics and Management/Leading High Performance Teams

Stakeholder Expectation and Definition/Stakeholder Requirements Definition/Managing Stakeholders

Facilitation

Decision Analysis

Coaching and Mentoring/Mentoring and Coaching/Coaching and Mentoring

Software Engineering

Acquisition Strategies and Procurement/Acquisition

Capability Engineering

Mission Needs Statement

System Environments/ External Relationships

Mission Level Assessment

Mission and Results Focus

Communication/ Communication/ Communication

NASA Interior and Exterior Environment

Negotiation/Negotiations

Organization

INCOSE Competency Framework

NASA Systems Engineering Competencies

NAVY SE Competency Model

Critical Thinking

Systems Thinking

Strategic Thinking

Problem Solving

Analysis/Logical Decomposition

Architecture/System Architecture/ Architecture Design

Modeling

Requirements/Technical Requirements Definition/ Requirements Management/ Stakeholder Requirements Definition/ Requirements Analysis/ Requirements Management

Product Integration/Integration/ Interface Management/Interface Management

Trade Studies

Figure 18. Comparison of ME Competency Framework with Other Competency Models

The most obvious insight from Figure 18 is that other frameworks only lightly address the foundational skills of their disciplines. For the Navy Competency model, only the specific discipline of software engineering is highlighted. The disciplines and domains that are required to develop missions and provide critical background to understanding the context in which those missions occur, are not often included in competency frameworks. But due to their prevalence in the dataset, they are included in the ME Competency Framework. It is worth noting that two of these competency models do address the acquisition context and its impact on the work.

The overlaps highlighted in Figure 18 are also critical to highlighting where mission engineering is related to other disciplines, in this case systems engineering. For example, the overlaps with the Mission Concept area demonstrate that general systems engineering is beginning to expand and incorporate mission-related elements. This is new in INCOSE – the Capability Engineering competency has been added for the soon-to-be-released competency model – but has been part of the NASA approach to systems engineering for longer. This is unsurprising as NASA has traditionally grown with a mission focus for its engineering efforts.

The systems engineering capability area has some clear overlap with SE competency models as expected. It is worth noting, however, that while a subset of the systems engineering competencies rose to the top of the ME Competency framework, Section 1 explains that there is a strong and clear relationship in the data between mission engineering and systems engineering. Therefore, there are a number of competencies contained in the other models that could be tailored inot the ME Competency Framework as appropriate.

4. VIEWS ON FUTURE DIRECTIONS FOR MISSION ENGINEERING

As mission engineering grows and matures, some changes are expected. The RT-171 team asked several questions of practicing mission engineers about their perspectives on the future. These are reported below, along with the team's interpretation of these responses in combination with the results of the literature review (Appendix D).

4.1 MISSION ENGINEERS' PERSPECTIVES ON THE FUTURE

The last set of questions used in the RT-171 interviews related to the expectations and future directions in mission engineering. In this particular section, four main questions where commonly explored. These include:

1. What is your vision for ideal implementation of mission engineering?

2. What has to change to make it a reality?

3. What do you see as the key risks to your organization developing the mission engineering workforce it will need five years from now?

4. What are the obstacles in obtaining these competencies?

Understanding Mission Engineering Future Directions (N=32)
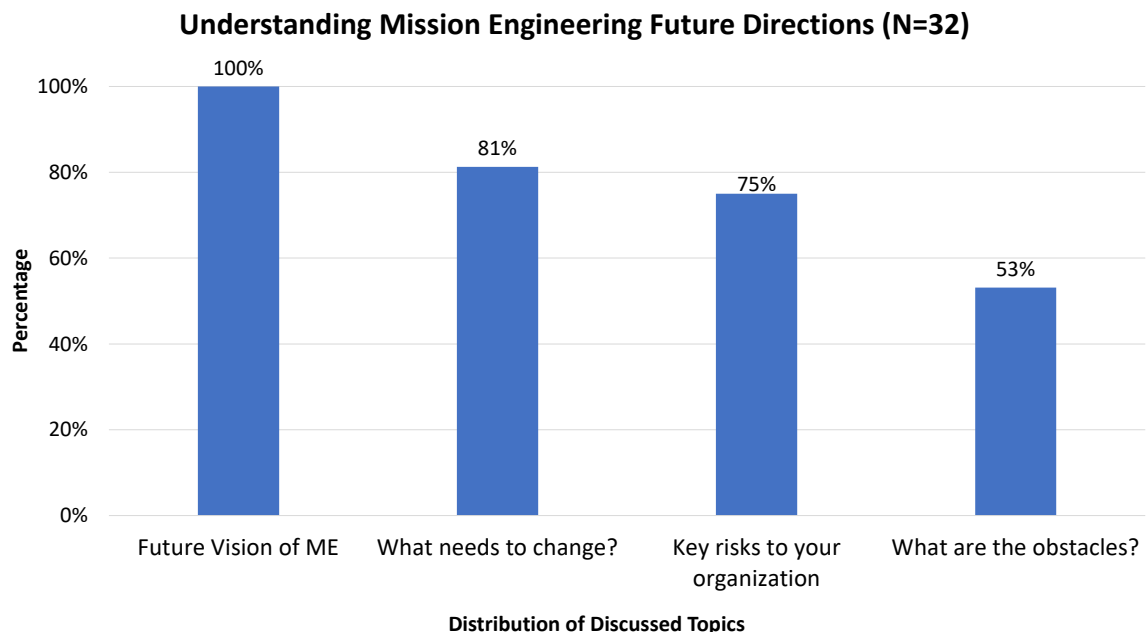
Figure 19. Distribution of responses for future direction in mission engineering.

Figure 19 illustrates the distribution of the responses to the above questions. As it can be observed, all the participants answered the question "What is your vision for ideal

implementation of mission engineering?". This question allows the understanding of the ideal state of mission engineering. The second most answered question (81%), What has to change to make it a reality?, aimed at understanding theoretical and practical gaps in the implementation of the mission engineering. Then, the third question (75%), What do you see as the key risks to you organization to develop mission engineering workforce?, provides insights on the current limitations in the development of a mission engineering workforce. Finally, the question "What are the obstacles in obtaining these competencies?" received 53% of responses. This question aims to facilitate the identification of key issues that practicing mission engineers believe are impacting the growth of a mission engineering workforce.

Once a general description of the mission engineering future directions dataset was presented, the next step is to understand each of these questions in greater detail. The methodology followed is based on a grounded theory approach, where topics emerged from the participants' responses, then related clusters of answers were coded.

The first question, *What is your vision for ideal implementation of mission engineering?*, was answered by the entire population of participants. Figure 20 presents the results of analyzing the transcripts of this question.

What is your vision for ideal implementation of mission engineering? (N=32)
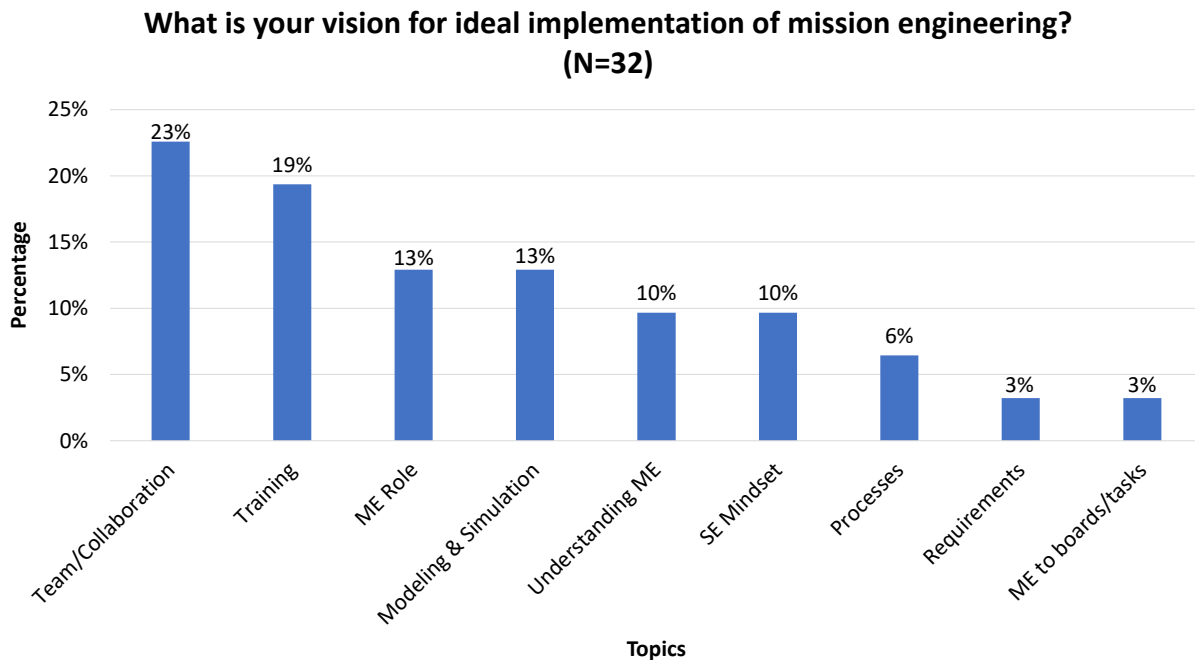
Figure 20. Distribution of responses for vision of mission engineering

From the frequency of topics presented the following items can be mentioned:
• Team/Collaboration. Interviewees recognize the need of having a team within the organization that focuses on mission engineering.
• More efforts are needed when training and educating the workforce.

- There is a need for a mission engineering role or the formal presence of an individual in charge of the mission.
- Establish a common understanding of mission engineering.
- Promote paradoxical thinking.
- Modeling & Simulation strategies at the mission level are needed.
- Processes that consider the mission should be developed and implemented.
- Requirements for defining what is needed to implement mission engineering should be defined.

Next, the question *What has to change to make this vision a reality?* was explored. As a reminder, this question receives 81% of responses. Figure 21 illustrates the distribution of responses.

What has to change to make it a reality?
(N=26)
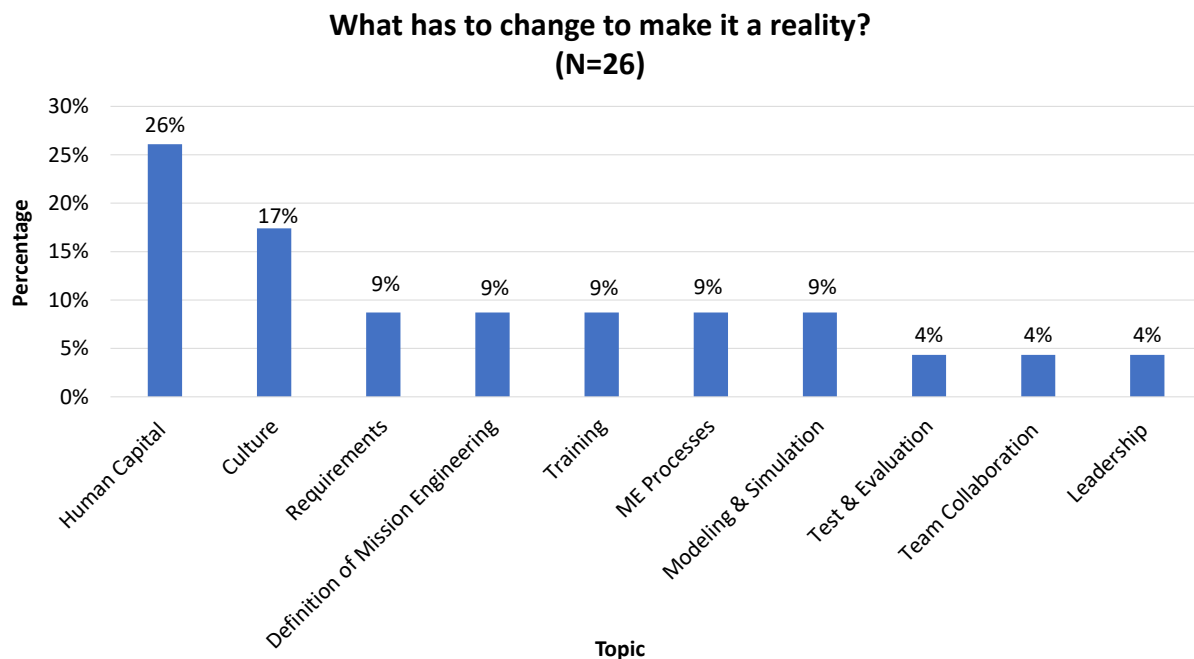
Figure 21. Distribution for responses to what has to change to make it a reality

From Figure 21, the following points can be extracted:
- Human Capital. The hiring of personnel is needed to support mission engineering operations. There are limited staff resources able to perform their operations at the mission level.
- Organizational Culture as it relates to the process on how the tasks are performed and the way in which personnel is hired.
- Efforts to develop mission based requirements should be initiated.
- A Book of Knowledge on mission engineering would facilitate common understanding of the domain.
- Training and educating the workforce on topics such as emergence and complexity.

- Processes should be standardized and embedded in current processes.
- Modeling and Simulation tools at the mission level are needed especially considering the evolution of the mission. Current frameworks seem to be obsolete.

The third question, *What do you see as the key risks to your organization developing the mission engineering workforce it will need five years from now?* received 75% of responses. Figure 22 presents the perceived risks to develop a mission engineering workforce.

What do you see as the key risks to your organization developing the mission engineering workforce it will need five years from now?
(N=24)

Figure 22. Distribution of responses to risks in mission engineering

From the above illustration, the following items can be extracted:
- Human Capital. The risk of finding the personnel with the right knowledge and aptitudes. The level of complexity mission engineering is tackling calls for people across multiple domains with very specific knowledge. Thus, multidisciplinary teams need to be built.
- Mission engineering is being addressed with processes that are obsolete due to the level of complexity at the mission level.
- Value of Mission Engineering. Participants mentioned that in some instances management does not recognize that value of ME, making its implementation and funding a challenge.
- Strong and supportive leadership is needed.
- Tools at the mission level are needed. Existing modeling and visualization are not able to cope with such levels of complexity.
- Culture risks. Relate to individuals not being confident and motivated to be effective. Willingness to step outside comfort zone.

- Lack of understanding of mission engineering principles.

Lastly, Figure 23 illustrates the most discussed factors that are limiting the acquisition of these competencies.

What are the obstacles in obtaining these competencies?
(N=17)
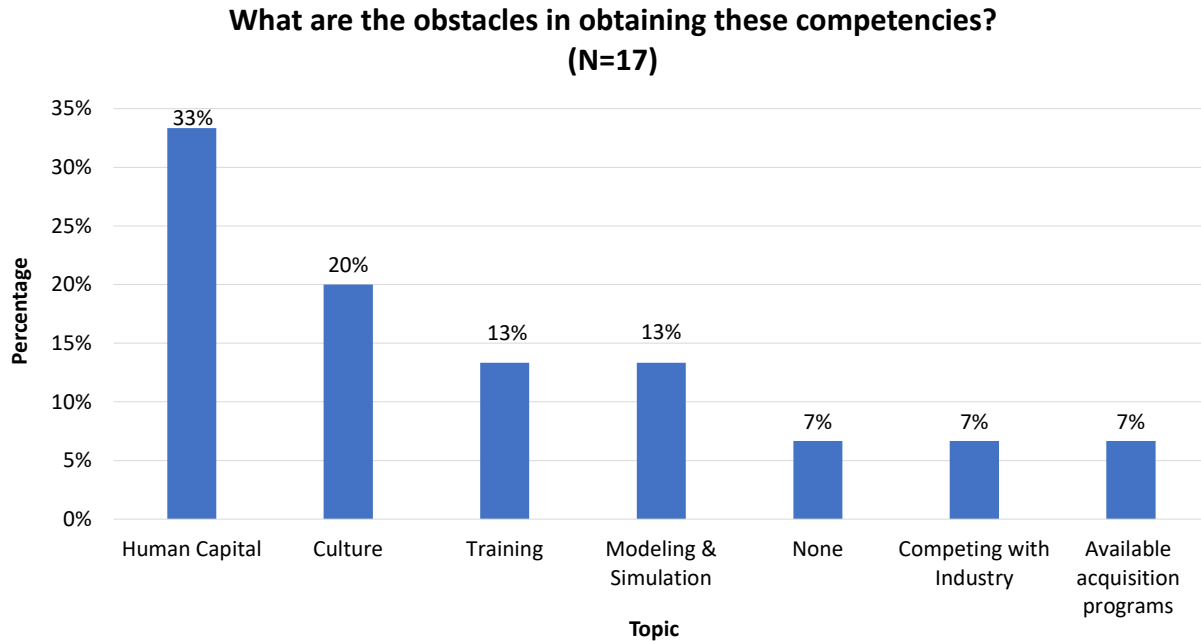
Figure 23. Distribution of responses to obstacles in obtaining the competencies

From Figure 23, it can be observed that:
- Human capital include those topics that influence, support or impact the performance of the individual. Lack of employee self-motivation was reported as an obstacle. In addition, further efforts on developing competencies are incentivized.
- It is difficult to implement any changes since the current culture resist to changes. A shift in the mindset of employees is mentioned.
- Training, there is a need to train systems engineering across multiple disciplines. Training in various domains is needed since the complexity of mission engineering projects is multidisciplinary.
- Modeling & Simulation. The architecture frameworks currently used are considered to be obsolete. Participants suggest transitioning to an enterprise level architecture than keep relying on static frameworks.
- Competition with Industry. It has been recognized that industry has a competitive advantage when recruiting talent. Nowadays, fewer individuals with strong analytical skills are attracted to the government job market, thus new strategies are needed when a attracting new hires.
- Current transition period thus there are less available acquisition programs.

4.2 MISSION ENGINEER'S FUTURE VISION FOR MISSION ENGINEERING

The future vision in Mission Engineering section was elaborated based on the response of 100% of participants.

A common agreement among participants is that efforts to have a common definition of mission engineering are needed. Items such a book of knowledge would serve as a reference point for an emerging community. Also, practitioner mission engineers foresee the development of mission engineering teams. There are limited to none instances of multidisciplinary teams that focus at the mission level, thus it is foreseen that new teams and partnership emerge when addressing mission level operations. Similarly, it is expected that current workforce receives training and incentives to understand mission concepts.

In addition, the mission engineering role has not being defined, thus it is expected that such role gains recognition as the discipline evolves. With respect to modeling and simulation techniques, tools and techniques dedicated to the mission level are expected to be available, existing methods are insufficient to cope with such levels of uncertainty and complexity. Lastly, the vision for mission engineering to be embedded into the processes.

In order to achieve such vision, experts recognize that mission engineering has to be discussed in multiple boards.

4.3 MISSION ENGINEER'S PERSPECTIVES ON FUTURE CHALLENGES

Identified pain points in mission engineering were classified into human capital, value of mission engineering, culture, and tools.

A central challenge is the common understanding of mission engineering. Multiple definitions and lack of knowledge make this discipline difficult to be valued. To promote and extend the discipline, experts suggest presenting mission engineering in multiple boards as well as the creation of a knowledge repository that serves a reference point.

Another common discussed challenge relies on the current workforce. Finding, training, developing and motivating the personnel is considered one of the major areas of opportunity in mission engineering. The level of complexity mission engineering is tackling calls for individuals across multiple domains with very specific knowledge, therefore personnel with the right knowledge and aptitudes should be hired. However, the discipline is not well recognized among practitioners or leadership so there is no motivation for stepping out from the comfort zone.

In addition, It is difficult to implement any changes since the current culture resist to changes. To complicate matters further, the competition with industry for individuals with strong analytical skills is bringing new challenges. Fewer candidates are considering a career in

government related projects due to the fact that government are considered be less competitive. Therefore, new strategies are needed when attracting new hires.

Lastly, the level of complexity of mission engineering makes existing processes and modeling and simulation tools obsolete. Experts suggest that visualization methods which include evolving scenarios are worth investigating.

CONCLUSIONS

Mission engineering is a relatively new and evolving discipline. The findings of this study were derived from interviews with 32 mission engineers, an extensive literature review, and examination of current academic courses in mission engineering. The data indicate that mission engineering is systems of systems engineering plus additional activities (stated by 70% of participants). The skills necessary for a mission engineer parallel the advanced technical skills of systems of systems engineering with more of an emphasis on operational domain knowledge.

The non-technical challenges for mission engineering were related to issues with the recognition of the importance of mission engineering's role in missions, having an organizational identity for mission engineering and acquiring the necessary funding and working through governance issues. The technical challenges include the operational context, requirements management and testing; not unsurprising for a systems-oriented acquisition discipline.

This study does not mark an endpoint on mission engineering but rather a waypoint. Some conclusions from this study are:

- Mission engineering needs to be funded as a unique organizational entity in operations or at least recognized as a separate discipline.

- There is a need for educating DoD personnel on what Mission Engineering is, but, in order to do that, more is needed in developing the appropriate coursework and materials. This is necessary for personnel in both the acquisition and operational contexts.

- Mission engineering as Systems of Systems Engineering requires personnel not only with strong technical skills in areas such as modeling and simulation but also strong interpersonal skills well integrated in the operational organizations.

- Acquisition needs to draw from the expertise of the mission engineers.

- More extensive studies need to further explore the processes of mission engineering and the skills and talents necessary for the process. This would include observing mission engineering in practice and further interview studies to continue the modeling of this discipline.

ACRONYMS AND GLOSSARY

ACRONYMS

AIA	Aerospace Industries Association
AIAA	American Institute of Aeronautics and Astronautics
DACAS	Digitally Aided Close Air Support
DARPA	Defense Advanced Research Projects Agency
DCGS	Distributed Common Ground/Surface System
DI2E	Defense Intelligence Information Enterprise
DoD	Department of Defense
DOTMLPF	Doctrine, Organization, Trainingl Materiel, Logistics, Personnel, Facilities
FAA	Federal Aviation Administration
IAMD	Integrated Air Missile Defense (Army)
IC	Intelligence Community
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering
ISR	Intelligence, Surveillance, Reconnaissance
MDA	Missile Defense Agency
ME	Mission Engineering
MORS	Military Operational Research Society
NASA	National Aeronautics and Space Administration
NDIA SED	National Defense Industrial Association Systems Engineering Division
NGA	National Geospatial-Intelligence Agency
NLCC	National Leadership Command Capability
NTSB	National Transportation Safety Board
PM	Project Management
SE	Systems Engineering
SoS	System of Systems

SoSE   System of Systems Engineering

UK MOD   United Kingdom Ministry of Defence

GLOSSARY

excerpt   a selection of interview data which addresses a specific topic or theme, which is identified by codes that highlight the specific content of the remark.

mission   the task, together with the purpose, that clearly indicates the action to be taken and the reason therefore (DoD 2017)

mission analysis   to understand a problem or opportunity, analyze the solution space, and initiate the life cycle of a potential solution that could answer the problem or take advantage of the opportunity (SEBoK 2017)

mission engineering   The deliberate planning, analyzing, organizing, and integrating of current and emerging operational and system capabilities to achieve desired warfighting mission effects (DAG 2017)

system   a functionally, physically, and/or behaviorally related group of regularly interacting or interdependent elements; that group of elements forming a unified whole (DoD 2017)

system engineering   a methodical and disciplined approach for the specification, design, development, realization, technical management, operations and retirement of a system (DoD 2017)

system of systems   a set of arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities (DoD 2017)

system of systems engineering   planning, analyzing, organizing, and integrating the capabilities of new and existing systems into a SoS capability greater than the sum of the capabilities of its constituent parts (DoD 2017)

APPENDIX A: RT-171 PUBLICATIONS AND PRESENTATIONS

Hutchison, N., G. Vesonder, D. Verma, H. See Tao, W. Miller. 2017. "Mission Engineering Competency." Presentation to the Northrup-Grumman INCOSE Community of Practice (COP), 23 August 2018.

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Vesonder, G., D. Verma, N. Hutchison, H. See Tao, W. Miller. 2017. "Development of a Defense Mission Engineering Competency Model." Proceedings of the 20th Annual National Defense Industrial Association (NDIA) Systems Engineering Conference, October 23-26, 2017, Springfield, VA.

Vesonder, G., D. Verma, N. Hutchison, H. See Tao, W. Miller. 2017. "Development of a Defense Mission Engineering Competency Model." Presented at the Systems Engineering Research Center (SERC)'s Annual SERC Sponsored Research Review, 7 November 2018, Washington, D.C.

Accepted for Publication
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APPENDIX C: DETAILED METHODOLOGY

The methodology for RT-171 was modeled after the RT-171 research methodology. The Helix project (currently SERC RT-173) has been ongoing since 2012 and has evolved over time a mixed methods methodology incorporating grounded theory and more traditional research approaches. Because the Helix research included exploration of the state of practice for systems engineering as well as the successful development of a competency (i.e. competency) model for systems engineering, this methodology was deemed appropriate for an analogous exploration of mission engineering.

The process and dataset are outlined in the sections below.

C.1   RT-171 RESEARCH PROCESS

The RT-171 research methodology discussed in the preceding section was deployed using the research process illustrated in Figure 24 below. The RT-171 research process consists of six major steps:
   A. Preparation
   B. Collection
   C. Analysis
   D. Answer Research Questions
   E. Publish Results
   F. Methodology Review
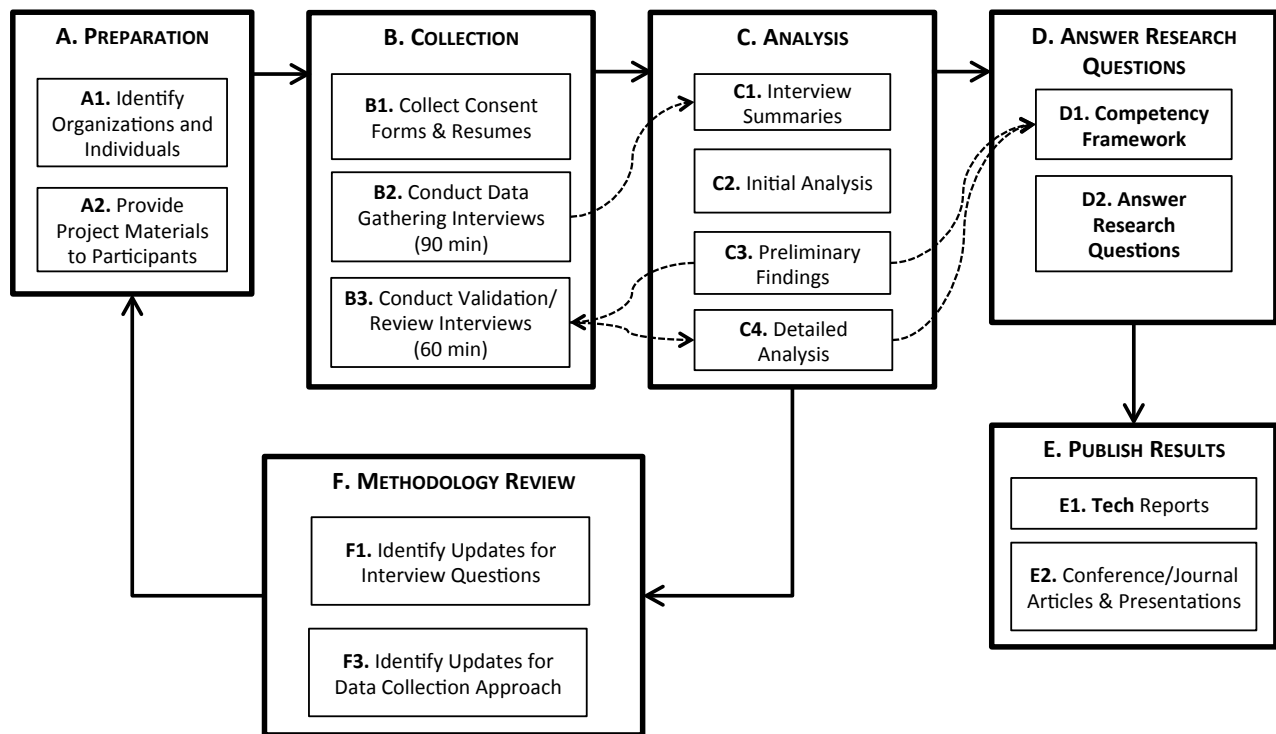
Figure 24. RT-171 Research Process

The focus of RT-171 was on executing the loop **A-B-C-F-A** multiple times with individuals from different organizations. The loop **B-C-B** was executed a few times when interviews were conducted with individuals considered thought leaders in mission engineering. In addition to performing the **A-B-C-F-A** loop with new individuals, steps **D-E** were executed that led to development of the preliminary findings in this report.

C.1.1 PREPARATION FOR DATA COLLECTION (A)

Preparation for data collection was the first step executed in the project. Initially, organizations from within the US DoD were identified for data collection; also, the primary focus was on mission engineers in these organizations (**A1**). As RT-171 progressed, non-DoD government organizations were added, as were thought leaders from non-governmental organizations. A project overview, including intent, purpose, and research objectives was provided to participants (**A2**).

C.1.2 DATA COLLECTION (B)

Following approved research protocols, a signed consent form is collected from the participants before conducting interviews (**B1**). Based on their willingness to participate in RT-171 interviews, individuals were scheduled at their convenience. Most of the efforts for 2017 were focused on gathering data from mission engineering practitioners (**B2**). The dataset is described in **Section C.2**, below. These interviews focused on a number of questions, covering a number

of areas such as:
- The definition and scope of mission engineering:
  - How the individual came to work in mission engineering
  - The individual and organization's definition and philosophy around mission engineering
  - Common processes and practices for mission engineering in the organizations
  - Overlaps between mission engineering and systems engineering
  - Critical activities in mission engineering
  - Critical challenges in mission engineering
- The critical competencies required for mission engineering:
  - Selection of individuals who will become mission engineers
  - Critical skills required for systems engineers
  - Qualitative value of critical skills, including how useful they have been personally and how common they are in the existing mission engineering workforce
- View on future directions for mission engineering:
  - Anticipated critical challenges and critical risks
  - Including what needs to change in order to meet these challenges

Interviews were no more than 60 minutes in length. The questions used in the interviews can be found in section C.1.3, below.

Finally, the team conducted interviews with individuals who were deemed to be thought leaders in mission engineering. During these interviews, current analysis and insights were shared and experts asked to provide their feedback and a general "sanity check" on the results.

Interview Questions
RT-171 utilized an informal interview style in which questions were used to prompt discussion, but interviewees were not rigidly required to answer only the questions as asked. Note that not all questions were asked of each interviewee. For example, someone who is currently practicing as a mission engineer might be asked a subset of these questions, while someone who is considered a thought leader around mission engineering, but is not currently practicing as a mission engineer, might be asked a different question set. Finally, the RT-171 often asked follow-up questions to probe on what interviewees had said. These were developed in real time and though they are not listed below, they are recorded in the team's interview summaries. The following is a summary of all interview questions that were used to prompt discussion in RT-171, grouped according to the general area of information being examined.

Mission Engineering
- Please describe how you got into mission engineering.
- In your own words, what is mission engineering?
- What is your [organization's] philosophy on mission engineering?
- What is your [organization's] process or approach to performing mission engineering?
  - How effective do you find this approach in practice?

- Do you see any overlap in the activities of systems engineering and mission engineering?
    - Are there elements of systems engineering that are particularly critical for mission engineering?
- What do you see as critical challenges in mission engineering?
- Please describe your current position. What are your key responsibilities?
- What is the key value you that you provide in this position?
- What is the most critical thing you do to be effective in your current position?

Competencies
- How do you identify/select the people who do mission engineering work in your organization?
- Are there critical skills you look for when selecting mission engineers?
    - Why are these skills important from your perspective?
[If Helix/*Atlas* proficiency model is used.]
- [Review of Atlas Proficiency Model]
    - Are any of the Atlas proficiencies critical for your job?
- What skills that are critical for mission engineering that aren't included in Atlas?
- Earlier you identified some key challenges for mission engineering. What skills are critical in helping you deal with these challenges?
- Of the skills you have identified that are important for mission engineering, which of these has been particularly helpful for you personally? Which of these critical skills do you think are most common in the current workforce?
- When you look at the people currently performing mission engineering in your organization, how well do you feel their skillsets align with the mission engineering skills you have defined?
    - For areas of misalignment or gaps, do you see ways that this can be improved?

Future Directions
- What is your vision for ideal implementation of mission engineering in your organization?
- What would have to change to make this a reality?
- What do you see as the key risks to your organization developing the mission engineering workforce it will need five years from now?
- What are the obstacles or challenges in obtaining these competencies?

C.1.3 DATA ANALYSIS (C)

The first step in data analysis is to prepare summaries of all interview sessions (**C1**). The RT-171 protocols do not include recording, so the team members all took notes. The team developed a comprehensive summary of each interview, which participants were given two weeks to review and edit. Initial analysis, typically which provides a very high level coding of the dataset

provides insights into additional questions to ask or ways that questions might need to be reworded to improve the results received. (**C2**). Because it took longer than expected to find schedule some interviews, the team took advantage of the time delay by developing preliminary findings based upon the data on hand and setting up analysis tools and queries so that as additional data was generated, it could be added into the existing infrastructure (**C3**). Detailed qualitative and quantitative analyses, using software tools as necessary, have been performed all the data that has been collected through RT-171 interviews (**C4**).

Coding

The interview dataset comprises summaries from 32 individuals. The RT-171 team uses qualitative data analysis, primarily through data coding. Coding is "a systematic way in which to condense extensive data sets into smaller analyzable units through the creation of categories and concepts derived from the data." (Lockyer 2004) Codes can be layered, and evolve over time, as explained below. The main type of coding done by the team is called "open coding", the purpose of which is to break down, compare, and categorize data (Strauss and Corbin 2014).

One of the strengths of the coding approach is that codes can overlap - individuals may discuss several issues together and researchers can layer multiple codes together. Not only does this help to give a true characterization of the data, but common patterns in overlaps may provide useful insights. Additional codes were then added to this subset of the data to further clarify the patterns. For example:

> The skill hardest to find is in the operations context. Training doesn't really work.

In this example, there are several areas of coding:
- The skill hardest to find is in the operations context. Training doesn't really work.
    - The statement that "operations context" is a difficult skill to find highlights that it is seen as a *valuable competency* for mission engineers.
- The skill hardest to find is in the operations context. Training doesn't really work.
    - The difficulty of finding individuals with operational context highlights a specific *workforce issue* in the interviewee's organization.
- The skill hardest to find is in the operations context. Training doesn't really work.
    - The statement that training does not work helps provide insight into the *career paths* for mission engineers. If this statement is true, then experiences in operational context are required to grow these skills.

By examining how often characteristics were cross-coded, it helped to identify relationships that participants believed are important across organizations. Figure 25 provides an example of the coding comparisons. The higher the bar, the higher the overlap in excerpts between codes. This provides the team with insight into relationships between and patterns around characteristics based on how interviewees discussed them.
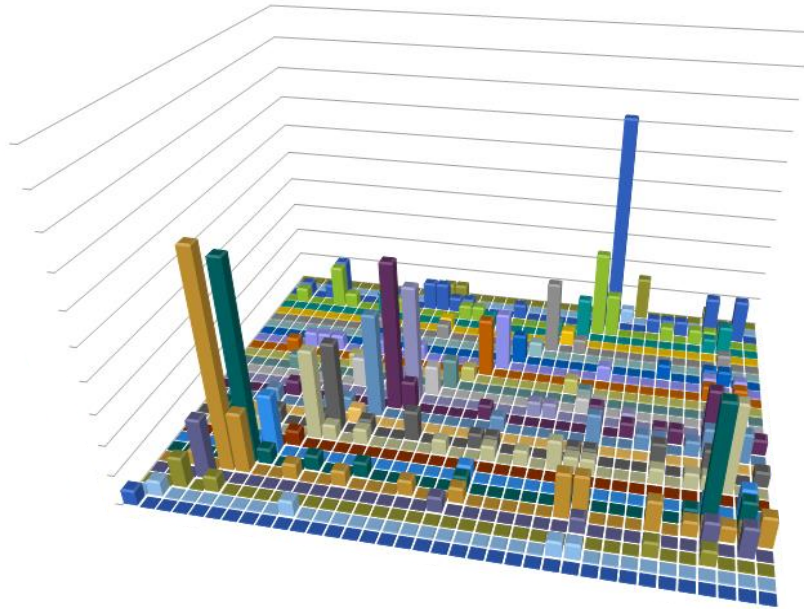
Figure 25. Example of Coding Relationships

The structure that emerged for mission engineering included many areas, one of which was competency. Initially, the competencies arose in three natural groups: technical, non-technical, and mindset-related. The team went through three levels of coding for each interview, as illustrated in Figure 26. The first pass identified all the portions of text (excerpts) that were related to competencies. These excerpts were all reviewed to identify whether the competencies described were technical, non-technical, or related specifically to mindset. Then each of these sets of excerpts was analyzed a third time to identify the specific competencies identified. Figure 24 provides just a few examples: these included everything from specific skills to understanding the context in whch mission engineering occurs.
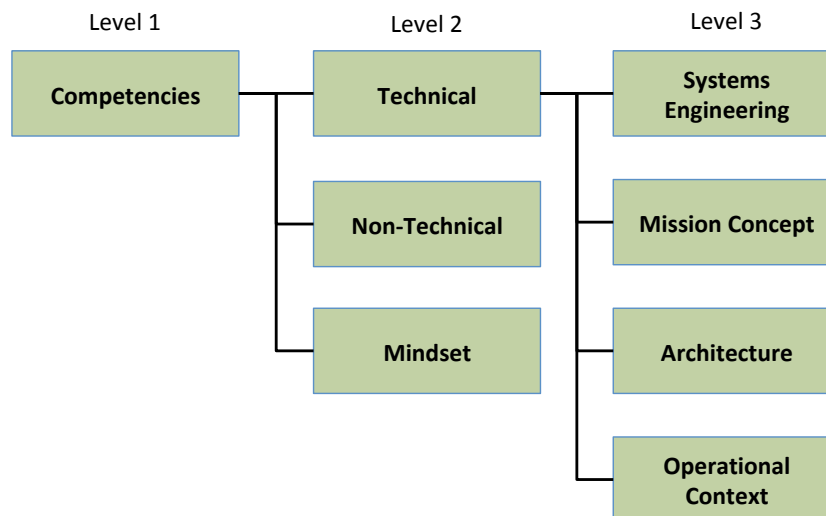
Figure 26. Example of Levels of Coding

The team then was able to drill down into the excerpts associated with each individual competency to identify how the competency is addressed, areas of concern, etc. And the coding was used to perform basic analysis of the dataset. (See Section 1, Section 4, and Appendix E).

Synthesis

The coding approach was critical to organizing and analyzing the data. To develop a competency framework, the team reviewed each of the individual competencies identified in interviews and look for patterns and natural groupings. This was informed by the literature review, and in particular the organization of other competency models that were reviewed. This is described in Appendix E.

C.1.4   ANSWER RESEARCH QUESTIONS (D)

The RT-171 team put a significant amount of effort into analyzing the interview data and combining it with the literature review results, to develop a preliminary understanding of an appropriate competency framework for mission engineering (**D1**). All analysis performed on data collection was intended to answer the RT-171 research questions on both broad and detailed levels (**D2**).

C.1.5   PUBLISH RESULTS (E)

Publishing reports and papers for public consumption is a key objective for RT-171 research. This report represents the key technical report publication for RT-171 (**F1**). All results and observations reported in RT-171 publishing are done in an anonymous aggregated manner. Nothing published by RT-171 is traceable to any particular individual or to an organization. In addition, peer-reviewed conference and journal papers have been submitted for publication for wide dissemination of RT-171 results. (**E2**).

A complete list of RT-171-related publications can be found in Appendix A.

C.1.6   METHODOLOGY REVIEW (F)

Data collection and analysis is being performed iteratively, as RT-171 continues to identify and visit organizations. After any site visit and before the next one, a review is conducted to identify any updates to the interview questions or process (**F1**).

C.2 DATASET

The current dataset for mission engineering comprises interviews with 32 individuals and the extensive literature review (see Appendix D, below for details on the literature review). Figure 27 shows the distribution by organization type.

Percentage of Participants by Organization Type (N=32)
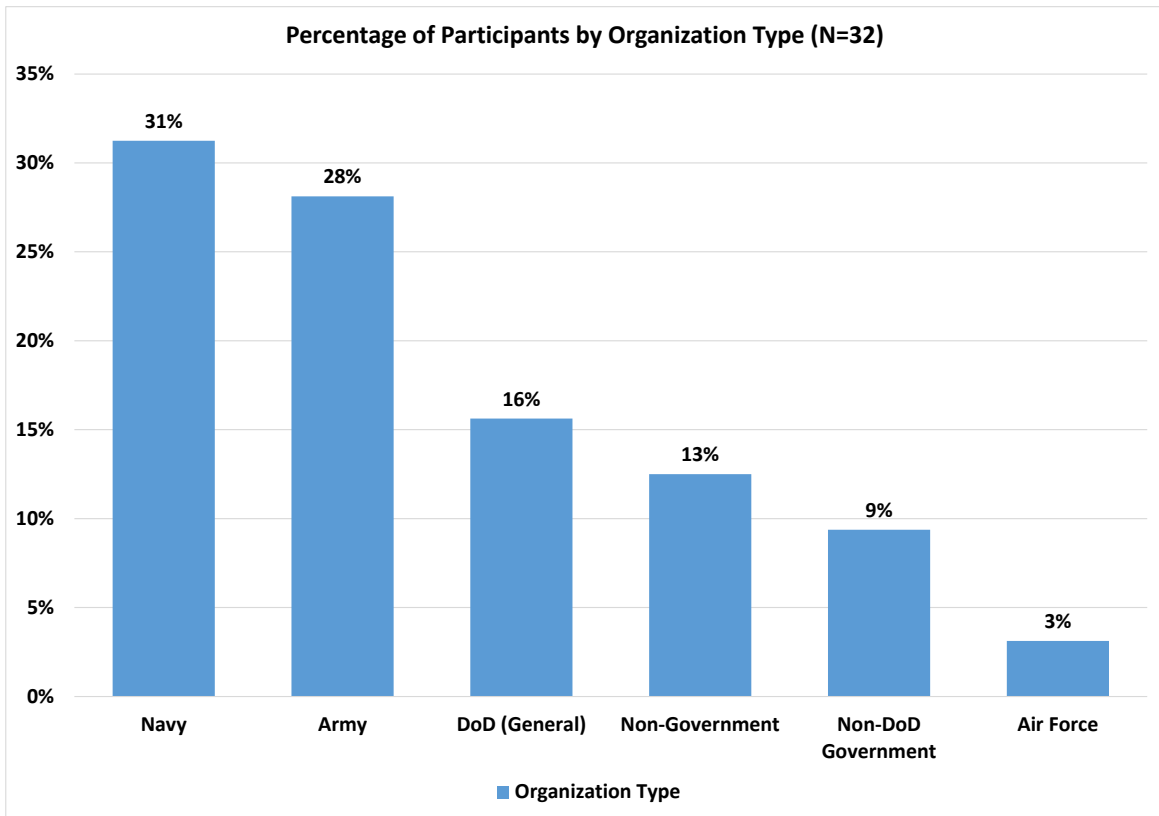
Figure 27. Percentage of Interviewees by Organization Type.

APPENDIX D: LITERATURE REVIEW

Mission engineering is a newly established practice in many US DoD and industry organizations that applies the mission context to system of systems and complex systems. Most current systems engineering practices do not fully address the unique characteristics of mission engineering, addressing the end-to-end mission as the 'system' and extending further beyond data exchange between the individual systems for cross-cutting functions, controls and trades across the systems. This section provides a background of system of systems engineering (SoSE) to better understand mission engineering as SoSE is applied in an operational context.

D.1 SYSTEMS ENGINEERING AND SYSTEM OF SYSTEMS: DEFINITION AND SCOPE

A system is defined as "a functionally, physically, and/or behaviorally related group of regularly interacting or interdependent elements; that group of elements forming a unified whole" (DoD 2008). SE is defined as a methodical and disciplined approach for the specification, design, development, realization, technical management, operations and requirement of a system. Traditional SE focuses on the development of systems with a stable architecture and static technologies. Under these principles, the manufacturing organization follows a vertical integration approach, meaning that it has complete control over all the interfaces needed for developing the system. It is also assumed that all system's requirements are known and can be frozen in time without affecting its performance (Azani 2008). Therefore, it is possible to anticipate and forecast the behavior of the system at any state.

The 21th century is recognized as the inflection point in the design, development, and maintenance of engineered systems. The introduction of individual workspaces to replace big calculators opened the door for less centralized management organizations. Partnerships and alliances led to a network of organizations that share knowledge and resources, and instead of relying in controlling the entire system lifecycle, they have transitioned from focusing on the production line to ownership of the data (Luzeaux, 2008). Also, evolving stakeholder needs and rapid changing technologies result in the inability of the system to operate in predetermined scenarios. Hence, systems are increasing in complexity due to: the participation of multiple stakeholders in the development of the system, their implementation in unanticipated scenarios, and to rapid evolving technologies (Azani, 2008, Luzeaux, 2008, Jamshidi, 2009).

Nowadays, systems engineers must deliver systems with self-organized and self-regulated capabilities. Systems must also be able to respond to evolving needs and rapid changing technologies (Azani, 2008). For instance, to support complex operations around the globe, the U.S. DoD shifted from a user needs approach to a capabilities based approach (Dahmann, 2008). The development of new capabilities relies in the combination systems, which must work together to meet the end objective. However, traditional SE practices are fixed and assume that systems do not evolve over time. Therefore, new strategies and approaches that consider the increase in complexity are needed.

Currently, the US DoD capabilities are provided by an aggregation of systems, also referred to as SoS. According to the US DoD, the definition of an SoS is "a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities (DoD, 2004). There are four types of SoS classifications that are required to understand and characterize the SoS based on the relationships of the systems within the SoS [Dahmann and Baldwin, 2008]:

- Directed SoS, where the integrated system-of-systems is built and managed to fulfill specific purposes. It is centrally managed during long-term operation to continue to fulfill those purposes as well as any new ones the system owners might wish to address.
- Virtual SoS, which lack a central management authority and a centrally agreed upon purpose for the system-of-systems.
- Collaborative SoS, where the component systems interact more or less voluntarily to fulfill agreed upon central purposes.
- Acknowledged SoS, which have recognized objectives, a designated manager, and resources for the SoS; however, the constituent systems retain their independent ownership, objectives, funding, and development and sustainment approaches.

There is a focus on acknowledged SoS in the US DoD as the warfighter capabilities are increasingly emphasized. Usually in the US DoD, multiple systems are required to meet the end-to-end capability needs. When a formal SoS is recognized based on its need, an organization is recognized as being responsible for the SoS area, including the general definition of the objective of the SoS. But this usually does not include the changes in ownership of the systems in the SoS or changes in the objectives of the constituent systems. Also, the current systems are still in use and needed for its original intent. This presents a challenge especially based on the hierarchical structures of the defense acquisition management.

D.2   SYSTEM OF SYSTEMS ENGINEERING: DEFINITION AND SCOPE

System of Systems (SoS) systems engineering (SE) "deals with planning, analyzing, organization and integrating the capabilities of new and existing systems into an SoS capability greater than the sum of the capabilities of its constituent parts (DoD, 2004). Without a mission operational context, there is a lack of direction or driving force to aid the developers and managers in determining which systems have to be involved, what functions they have to perform, and how the operators or users will make use of these systems. This research effort provides the additional value of facilitating an improved understanding of the increasing complexities in SoS.

According to numerous sources, the differences between systems and systems of systems as applied to systems engineering were considered based on management and oversight, operational focus, implementation, and engineering and design considerations, as shown in Table 12 (Dahmann and Baldwin 2008 and Neaga et al. 2009).

Table 12: Comparison between Systems and Systems of Systems as Applied to Systems Engineering (Dahmann and Baldwin 2008 and Neaga et. al., 2009)

	Systems Engineering (SE)	Systems of Systems Engineering (SoSE)
Management and Oversight		
Stakeholder Involvement	Clear set of stakeholders	Multiple levels of stakeholders with mixed and possibly competing interests
Governance	Aligned management and funding	Added levels of complexity due to management and funding for both SoS and systems; SoS does not have control over all constituent systems
Operational Focus (Goals)		
Operational Focus	Designed and developed to meet common objectives	Called upon to meet new SoS objectives using systems whose objectives may or may not align with the SoS objectives
Implementation		
Acquisition/Development	Aligned to established acquisition and development process	Cross multiple system lifecycles across asynchronous and development efforts, involving legacy systems, developmental systems, and technology insertion
Process	Well-established	Learning and adaptation
Test and Evaluation (T&E)	Test and evaluation of the system is possible. System requirements drive the system T&E and use Measures of Performance (MoP)	Testing is more challenging due to systems' asynchronous life cycles of component systems and the complexity of all the parts. At the SoS level, Measures of Effectiveness are needed, which are difficult to define, as well as MoPs
Engineering and Design Considerations		
Boundaries and Interfaces	System of Interest (SOI) is defined by focusing on boundaries and interfaces	The dynamic and reconfigurable nature of SoS mean that boundaries are interfaces may change. Also, component systems may belong to more than one SoS and have variable availability
Performance and Behavior	Performance of the system to meet performance objectives	Performance across the SoS that satisfies SoS capability objectives while balancing needs of the constituent systems
Metrics	Derivation from requirements is straightforward	Difficult to define, agree, and quantify due to independent management of component systems

The initial key SoS SE artifacts were identified with the purpose of developing a set of approaches to apply SE to SoS by understanding the use of the SE artifacts and how they were used in SoS SE (Dahmann et al., 2010). In order to apply SE to SoS, the characteristics of SoS and their impact on the SE processes need to be understood. Based on the US DoD *SE Guide for SoS*, the SoS systems engineers focus on the core elements listed below as multiple existing and emergent systems are evolving and assembled to meet the capability objectives:

"In SoS SE, systems engineers are key players in the core elements of: (1) translating SoS capability objectives into SoS requirements, (2) assessing the extent to which these capability objectives are being addressed, and (3) monitoring and assessing the impact of external

changes on the SoS. Central to SoS SE is: (4) understanding the systems that contribute to the SoS and their relationships, (5) developing an architecture for the SoS that acts as a persistent framework for (6) addressing SoS requirements and solution options. Finally, the SoS systems engineer (7) orchestrates enhancements to the SoS, while monitoring and integrating changes made in the systems to improve the performance of the SoS." (U.S. DoD SE Guide for SoS, 2008)

Figure 28 illustrates the SoS SE artifact that was developed as part of an International SoS SE project under The Technical Cooperation Program (TTCP). Figure 28 is also described as a trapeze model that provides a conceptual view of SoS SE. However, it is not very useful to practitioners to help them develop an implementation approach.
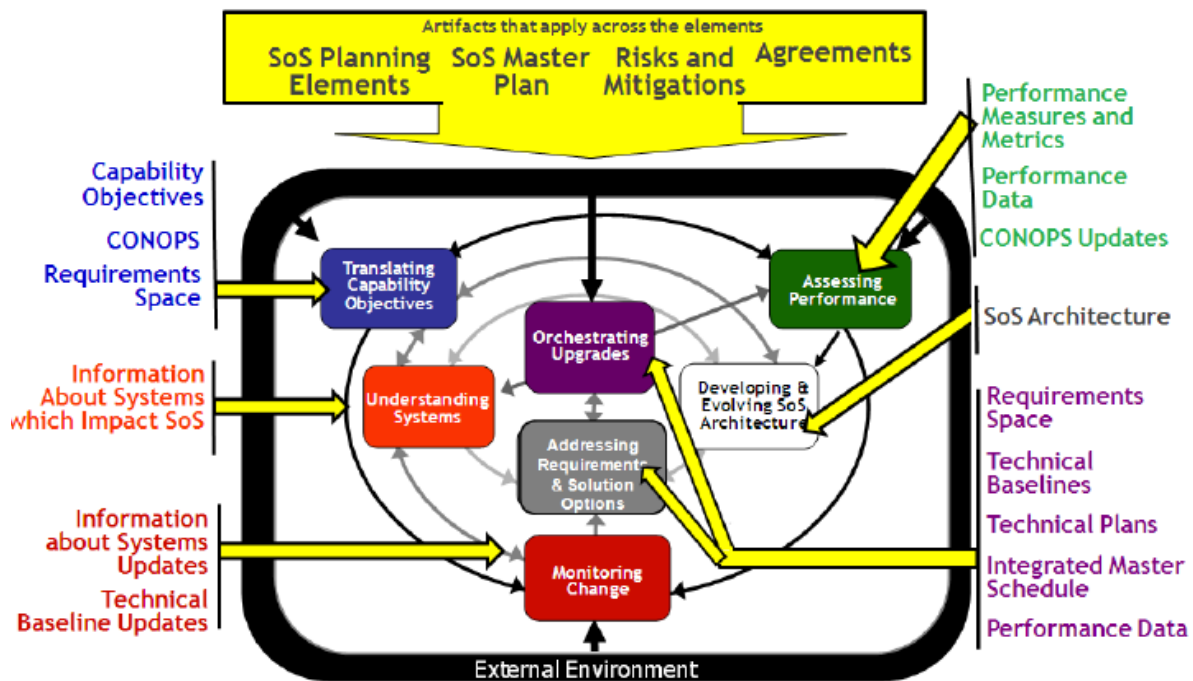

Figure 28: Artifacts in the Context of Core Elements of SoS SE (Dahmann 2010)

There was an initiative to develop the wave model based on the SoS SE artifact. In the wave model, the main SoS activities are the following: a) SoS Analysis, b) SoS Architecture, c) Plan for update, and d) Implement SoS update for (Dahmann 2012). The SoS wave model in Figure 29 was developed to "unwind" the trapeze model and provide an intuitive view of SoS SE in terms of successions of major steps in implementing an SoS SE process. This SoS SE wave model is built based on 'wave planning' for complex systems management by Dombkins. (Dombkins 2007 and Dahmann et al. 2011)
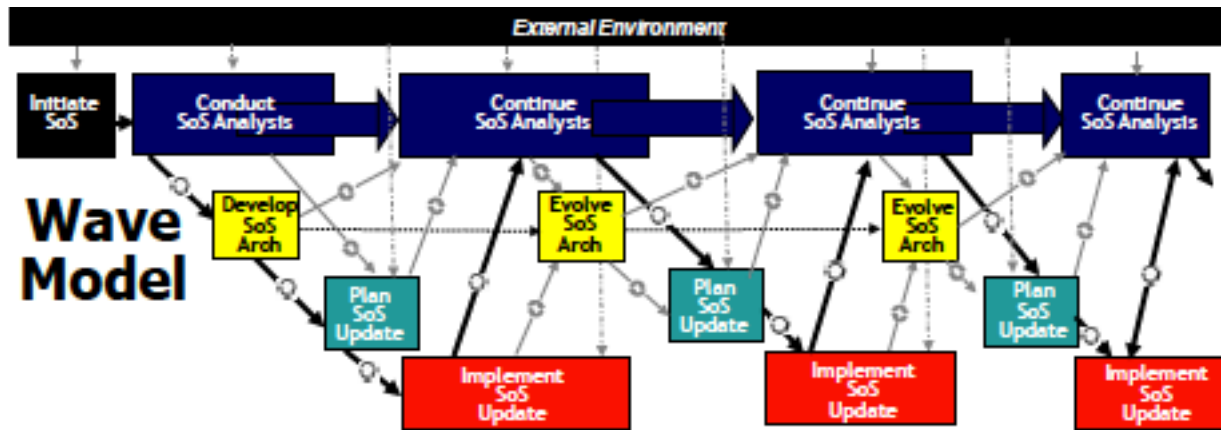
Figure 29: SoS Wave Model (Dombkins 2008 and Dahmann et al. 2011)

As the SoSE wave model is applied to mission engineering, the major steps in implementing an SoSE process are described in Table 13 (Dahmann, et. al., 2018). The colored boxes in Table 13 correspond to the respective elements in the SoSE wave model in Figure 29. This literature review finding of the critical mission engineering activities correlate to the research findings from the interview participants, as reported in Section 2.2.5.

Table 13: SoSE Wave Model Applied to Mission Engineering (Dahmann et. al. 2018)

Conduct SoS Analysis	**Define the mission** including mission threads and mission context (*including mission objectives, CONOPS, scenarios, key functionality, threat*)
	Identify current systems supporting the mission and how they are employed *(how is the mission implemented now?)*
	Assess mission performance to assess how well current systems work together to meet the mission objectives
	Identify gaps from a mission effectiveness perspective and fault isolate the source of gaps
Develop SoS Architecture	**Identify and assess options** for improving the mission effectiveness *(including changes on how the systems are employed as new or different systems, systems updates and non-material considerations)*
Plan SoS Update	**Guide systems acquisitions,** from requirements through implementation to test and maintenance to assure effective mission execution
Implement SoS Updates	Conduct mission level **integration and testing**
	Monitor mission effectiveness with changes in mission context, scenarios and threat capabilities

Due to the distinctive characteristics of SoSE, there are implications to the SoS testing and evaluation (T&E). Dahmann et. al. (2010) reviewed the SoS characteristics as they impact the T&E, as well as how it was being addressed in the SoSE community of practitioners. In terms of the implications of the SoS T&E on the management and oversight of SoS, Dahmann et. al. (2010) found it more difficult to establish the validation criteria and also harder for the governance to explicitly impose SoS conditions on system T&E. The operational environment of the system level may not have a clear equivalence in SoS conditions that require T&E. For the implementation aspect, the SoS T&E depends on testing of the constituent systems to SoS

requirements, and extends towards SoS level testing. It may be hard to bring multiple systems together in synchrony across the capability evolution for T&E. Finally, for engineering and design considerations, there may be increased subjectivity in assessing the performance and behavior of the SoS and additional test points may be required to confirm the behavior of the SoS (Dahmann et. al., 2010).

Since this study focused on critical mission engineering activities, development planning is considered as one of the key mission engineering tasks. Development planning is "the engineering analyses and technical planning activities that provide the foundation for informed investment decisions on the path a materiel development follows to meet operational needs effectively, affordably and sustainably"(DAG, 2017). Considering that most SoS development is evolutionary, continuous monitoring is required and changes will be made as updates on the SoS, as shown in the SoSE wave model. The mission context encompasses a complex environment that requires strategic development planning that may evolve over time based on the capability needs and changes in system.

As the mission-focus on SoS efforts have emerged in the past five to six years, the U.S. DoD engineering community can now successfully assess and determine which systems are relevant to a capability and how to modify these systems to support critical mission areas such as close air support, ballistic missile defense, and satellite communications. To address the application of SE to SoS, the DoD Guide to SE for SoS (2008) and the International Organization for Standards/ International Electrotechnical Commission/ Institute of Electrical and Electronics Engineers (ISO/IEC/IEEE) 15288, Appendix G are used as guidelines.

D.3   CAPABILITIES ENGINEERING

D.3.1   PERSPECTIVES

The term **capability** is widely used across many industrial sectors and has begun to take on various specific meanings across, and even within, those sectors. Terms such as capability-based acquisition, capability engineering and management, life capability management, capability sponsor, etc. are now ubiquitous in defense and elsewhere. Henshaw et al. (2011) have identified at least eight worldviews of capability and capability engineering and concluded that the task of capability engineering is not consistently defined across the different communities.

Whilst most practitioners recognize that there is a strong relationship between capability and system of systems (SoS), there is no agreed upon position. However, there are two beliefs that are widely accepted among the different communities, including:
- a capability comprises a range of systems, processes, people, information and organizations. (i.e. a system at levels three through five in Hitchin's (2003) five layer model, such as a Carrier-Strike capability) and
- the capability is an emergent property of SoS (i.e. the capability of Carrier-Strike to engage targets within 300 miles of the sea.)

D.3.2   SERVICES VIEW OF SYSTEM OF SYSTEMS ENGINEERING

The *Guide to the Systems Engineering Body of Knowledge* (SEBoK) has the following to say about service-oriented systems of systems (BKCASE Authors 2017):

> *A system of systems (SoS) is typically approached from the viewpoint of bringing together multiple systems to provide broader capability. The networking of the constituent systems in a SoS is often a key part of an SoS. In some circumstances, the entire content of a SoS is information and the SoS brings together multiple information systems to support the information needs of a broader community. These information technology (IT)-based SoS's have the same set of characteristics of other SoS's and face many of the same challenges. Currently, IT has adopted a 'services' view of this type of SoS and increasingly applies a International Organization for Standardization (ISO) 20000 series (Information technology -- Service management) or Information Technology Infrastructure Library (ITIL) v. 3 (OGC 2009) based approach to the design and management of information-based SoS. A service perspective simplifies SoSE as it:*
> - *is a more natural way for users to interact with and understand a SoS,*
> - *allows designers to design specific services to meet defined performance and effectiveness targets, and*
> - *enables specific service levels to be tested and monitored through life.*
> *Although it has not been proven to be universally applicable, the services view works well in both IT and transportation SoS.*

D.4   RELATIONSHIP BETWEEN SYSTEM OF SYSTEMS AND MISSION ENGINEERING

> *All models are wrong, but some are useful.* – George Box

As language is but a model for reality, it is limited in its precision and quite often usefulness. The meaning of language is critically dependent upon its context and the lens of the one who uses it. Creating a specific definition or even description of a phenomenon that is interpreted in exactly the same way by all observers may not be possible. One could argue that it is only in mathematics that this is possible, and only possible when the mathematics are not intended to correspond with our phenomenological reality. Thus, it is not surprising that there is confusion around the meaning of terms such as "systems of systems" and "mission engineering". However, it is possible to gain an understanding of the roles that these terms may play in how people understand various phenomenon.

Those who intend to conceive, design, build and use systems generally do so for (a) a purpose, and (b) with the intention for these systems to work in certain contexts (which includes the system itself). It is difficult to imagine a systems discussion in which both of these, the system behavior and the system context, are not relevant. Quite often, those who are only aware of a single context may lose sight of the boundaries and limits of such a context, much the best way

to understand a culture often comes from the observations of those who are from a different culture. Frequently, misunderstanding may occur due to differences in the unspoken, perhaps unappreciated, differences in context. Therefore, it might be of value to consider the terms 'Systems of Systems' and 'Mission Engineering' qualitatively with respect to the notions of purpose and context.

Figure 30 constructs a space with increasing complexity in context in the vertical axis and increasing complexity in effect in the horizontal axis. One can use this taxonomy to analyze the construction and behavior of systems over time in a number of domains. Clearly, systems that are simple in nature with simple expected behaviors are well-understood and subsequently are not of much interest in this discussion. With limited expectations in use and construction, systems can be thought of as simple. Systems get interesting, which is to say unpredictable, when the expectations of context and use become more complex.

As an example, consider the automobile industry. The expected outcome is to design, development, manufacture and sell automobiles at a profit. To reduce uncertainty, and to maximize profit at the time, Ford Motor Corporation became a vertically oriented company and did everything from mining the ore, to making the steel, to building and selling the cars. [3]However, over time, this became a far less successful strategy economically as single companies were not capable of maintaining technical or economic leadership is such a vast array of supporting technologies. As a result, the overall context for the system creating the cars became ever more complex. Being successful in the automobile industry involved being a master of the supply chain. While one could argue that this provided far less control over the 'system', it supported a marketplace economics that enabled far greater capabilities. The automobile industry, and the exquisite supply chain with its distributed control, became a 'system of systems' in that no one entity had the level of control of an integrated industry. On Figure 30, this is shown as the move up from the lower, far right quadrant.

A very different example is the often-referenced Apollo program. In this case, the desired outcome is not a product, but rather is a singular outcome, that putting a man on the moon and returning him home safely before the end of the decade. As this was seen as a mission of existential importance, the Apollo program had a great deal of control over its operations. In fact, it almost single-handedly created a new industry in micro-electronics and drove the development of numerous critical technologies.[4] The designers of Apollo determined the requirements of the system, the subsystems and its components and it was up to the suppliers (as well as the astronauts) to support them. Apollo can be shown in Figure 30 as a movement to the right from the lower left quadrant. Defense actions and campaigns can be seen in much the same way, where the complexity can be seen in the range of the desired effects. However, in the military, the range in desired effects was often supported by the human element as the

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[3] http://www.economist.com/node/13173671, 3/27/2009, Moving on up, Is the recession heralding a return to Henry Ford's model?

[4] https://www.computerworld.com/article/2525898/app-development/nasa-s-apollo-technology-has-changed-history.html, July 20, 2009, NASA's Apollo technology has changed history, Apollo lunar program made a staggering contribution to high tech development.

glue that could be used to tie all of the pieces together. For example, in the navy the commanders of vessels could make decisions that were communicated across the fleet through flag men and other human elements. However, as more of these operations are supported by technology, the systems missions requirements need to be more carefully planned for future operations.

What is interesting is that both commercial industry and defense are moving to the quadrant in the upper right which is one of high complexity both in mission and in context. For industry, the changing notion of systems with increased autonomy and virtualization has dramatically increased the importance of delivered services. For example, in the automobile industry, the increased use of autonomy may make the delivery of an automobile obsolete when the service of mobility becomes far more relevant. The notion of automobile ownership may become far less important as the automobile becomes a 'component' in the mobility system of autonomous Uber and Lyft. Likewise, it is no longer possible for the military to be the predominant force in technology development as was done with Apollo, or even to have dedicated capabilities for all of this missions and forces. The net result is the context of systems of systems in which control is traded off for increase capabilities at a lower cost. Thus, both commercial industry and defense will need to master complexity in both of these dimensions.

Rather than attempting to determine the differences between 'systems of systems' and 'mission engineering', this discussion shows how these terms can be used to describe context and range of intent. Making these distinctions can provide the means to discuss the challenges and concerns in each of the quadrants shown in Figure 30, and allow for the analysis and discussion of decisions and actions throughout this space.
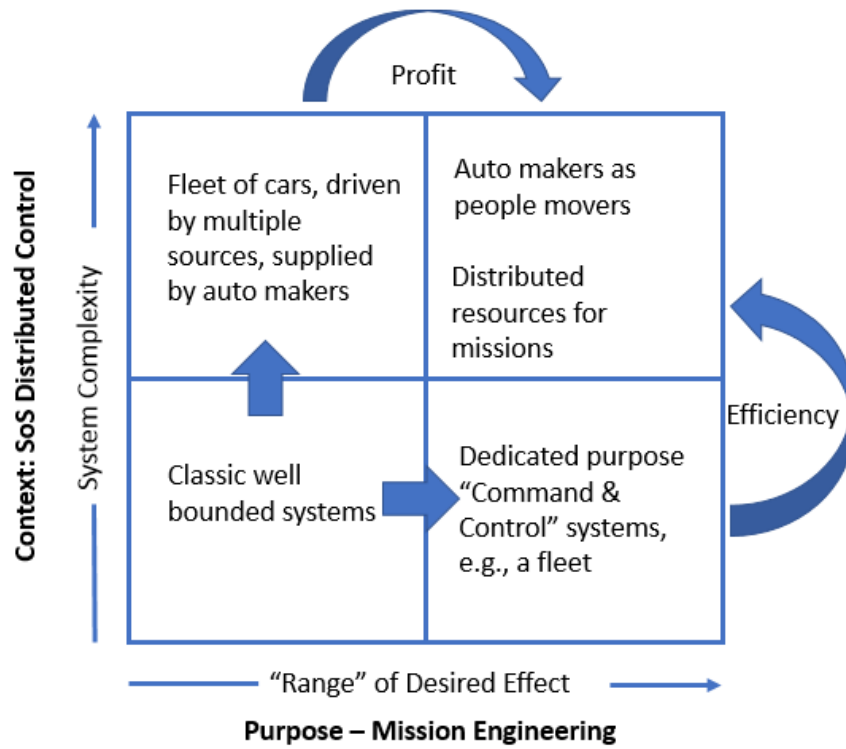
Figure 30. Relationship between Mission Engineering and System of Systems Engineering

As described in the methodology, the team coded the data several times to develop a rough structure of competencies. In total, there were 1834 excerpts around competency across the dataset, as highlighted in Figure 30. Every individual who participated (N=32) discussed mission engineering competencies as part of their interviews:

- 100% of interviewees (32) described technical competencies

- 94% of interviewees (30) described non-technical competencies

- 91% of interviewees (29) described mindset-related competencies

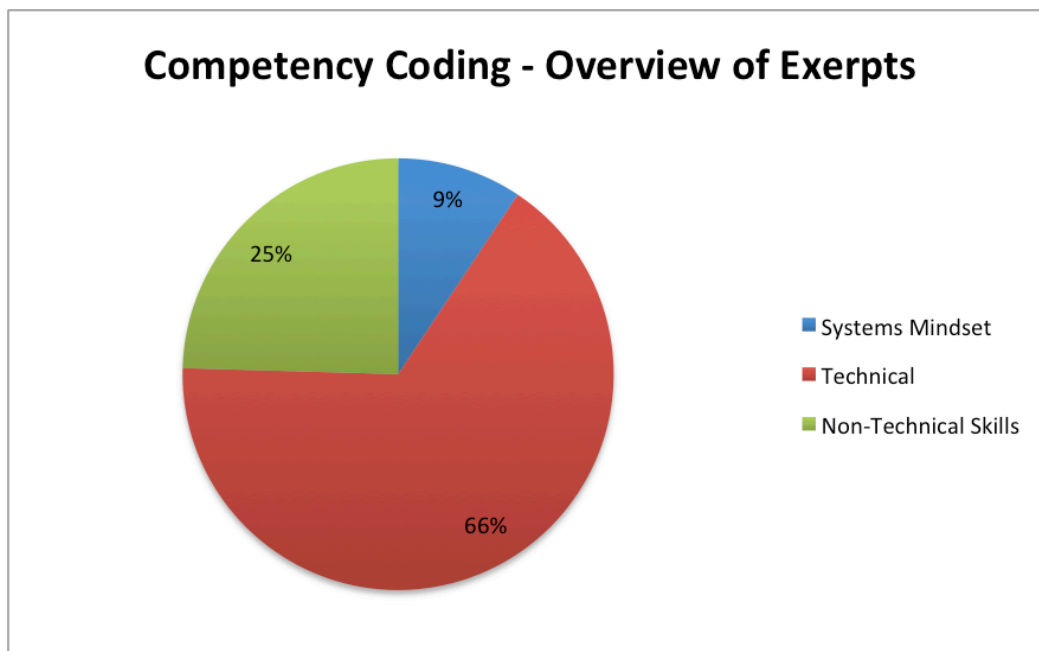The breakdown of individual excerpts into these groups can be found in Figure 31.

**Figure 31. Percentage of Competency Excerpts around Specific Types of Competencies (N=1834)**

E.1 TECHNICAL COMPETENCIES

There were a total of 47 individual technical competencies identified across 1106 excerpts, ranging from competencies such as "risk management" to "mission design" to "domain knowledge". Once these were identified, the team reviewed the competencies to determine appropriate groupings for the competencies as well as any appropriate cut-offs. For example, if a competency was described only once by a single interviewee, and does not align with competencies found in related competency models, the team deemed that it did not make sense to incorporate it into the ME competency model.

The three groupings for technical competencies – which align with competency model described in Section 3:

- Discipline and Domain Foundations

- Mission Concept

- Systems Engineering Skills

Because the co-coding approach means that several competencies might be addressed together, there are a total of 1106 excerpts for technical competencies, but only 847 of these were unique (i.e. 259 of the excerpts were coded across multiple competencies and, therefore, are counted more than once in the total excerpts). Figure 32 shows the aggregation of the 847 unique excerpts into the competency areas reflected in the ME Competency Framework (Section 3).
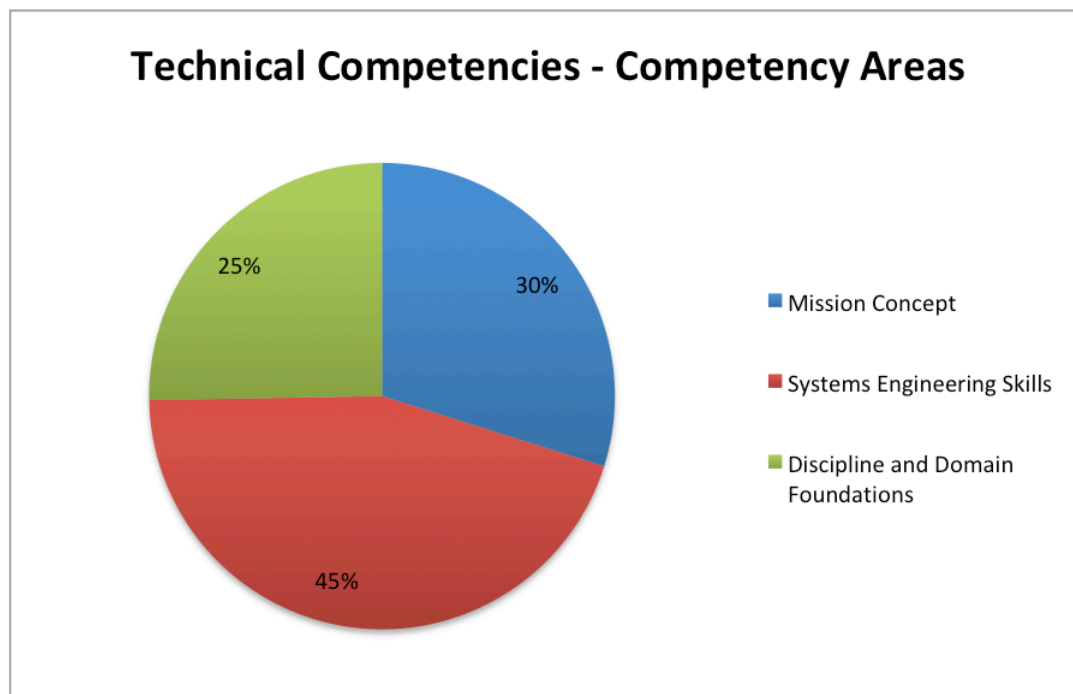

Figure 32. Technical Competencies Exerpts Aggregated into Competency Areas (N=847)

Each of these competency areas – and the skills associated with them is described in additional detail below.

E.1.1 DISCIPLINE AND DOMAIN FOUNDATIONS

Many of the technical competencies described foundational skills, which provide mission engineers a grounding in technical skills that enable them to act as technical leaders in mission engineering. Figure 33 provides an overview of the competency categories identified from these competencies as reflected in the ME Competency Framework (Section 3).
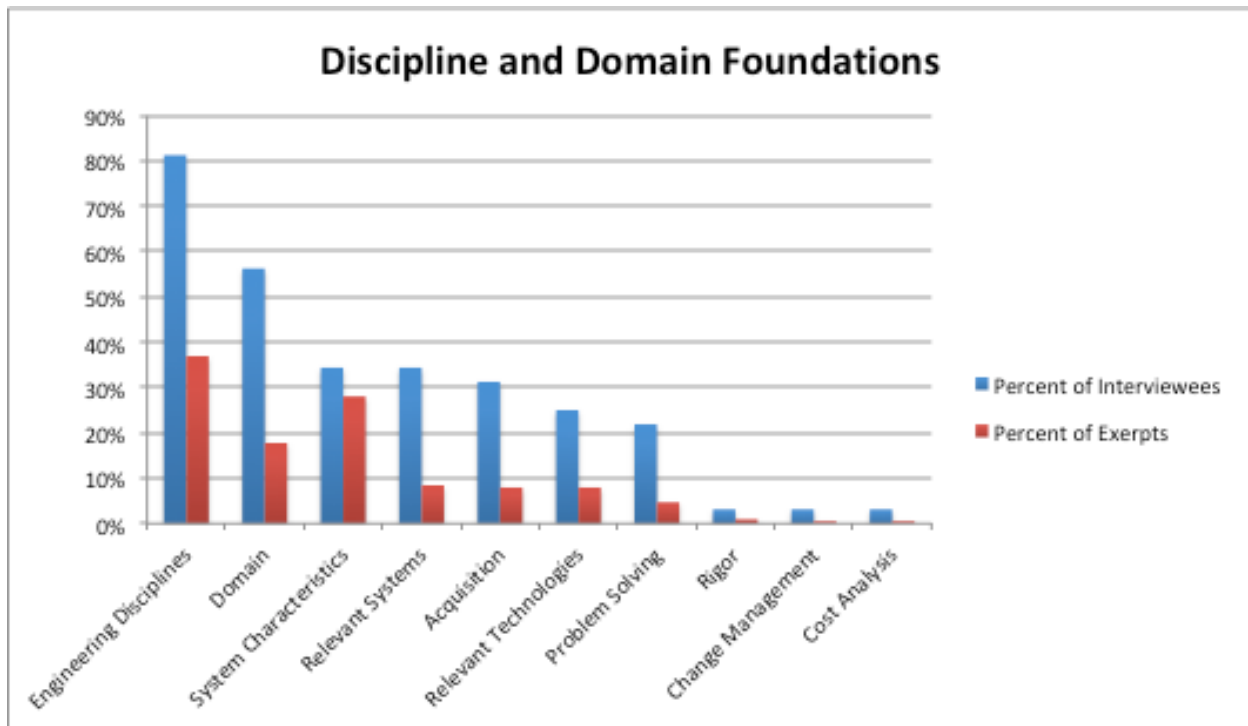
Figure 33. Discipline and Domain Competencies (N=32 interviewees; 214 excerpts)

Note that some of these categories represent a recombination of individual competencies. For example, "Engineering Disciplines" is a combination of 3 individual competencies described by interviewees:

- Engineering disciplines (which were described either generally, i.e. "having a foundation in an engineering discipline is important" or highlighting a specific discipline, i.e. "electrical engineering is really important for our mission")

- Breadth across disciplines (e.g. it is critical for mission engineers to be able to understand enough of the engineering disciplines to be able to translate mission-related concerns to engineers or to understand the engineering solution well enough to understand the potential impact(s) on a mission)

- Appropriate depth (e.g. having enough depth in an engineering discipline to have credibility and general technical understanding)

Each of these is related to view that there is a critical foundation in an engineering discipline for a mission engineer. For the purposes of the ME Competency Framework, these were combined, though the balance of breadth and depth is described in the Framework itself.

"Problem solving" was highlighted as an important competency (cited by 21% of inteviewees, but in less than 5% of the excerpts on technical competency). Problem solving was cited in the data as an enabler to dealing with engineering, technology, and systems issues. Because this

represented a small set of the data and it was described as an enabler to other competencies, it is not expressly highlighted in the ME Competency Framework.

Likewise, "rigor", "change management" and "cost analysis" were cited, but each was meantioned by only 1 participant. Because of these, they are reflected in the data analysis but did not rise to the threshold of being included in the ME Comptency Framework.

This analysis gave rise to the first ME Competency Area: Discipline and Domain Foundations, which has six categories, as described in Section 3:

1. Principle and Relevant Disciplines

2. Relevant Domains

3. System Characteristics

4. Relevant Systems

5. Relevant Technologies

6. Acquisition Context

E.1.2 MISSION CONCEPT

All of the interviewees described critical competencies that the team has identified in the Mission Concept area. In total, there were 235 excerpts that described critical competencies related to the mission concept, as reflected in Figure 34.

By far, the most commonly-cited category in this area is related to being able to understand, work within, and describe the impacts on a mission from operational context. Operational context is the combination of the conditions, circumstances, and influences that will determine which systems will be used. This was cited by 90% of interviewees and made up over 60% of the total excerpts related to Mission Concept. It is worth noting that, in general, this competency tended to come from former operators, rather than by training engineers in operations. As one interviewee explained, "We have a mix of operators and engineers. It's really important because they give and take potential technical solutions, and have the opportunity to interact with the solutions, how it's automated or not, how it's needed versus how it operates." This was a common model for incorporating operational context into ME teams.
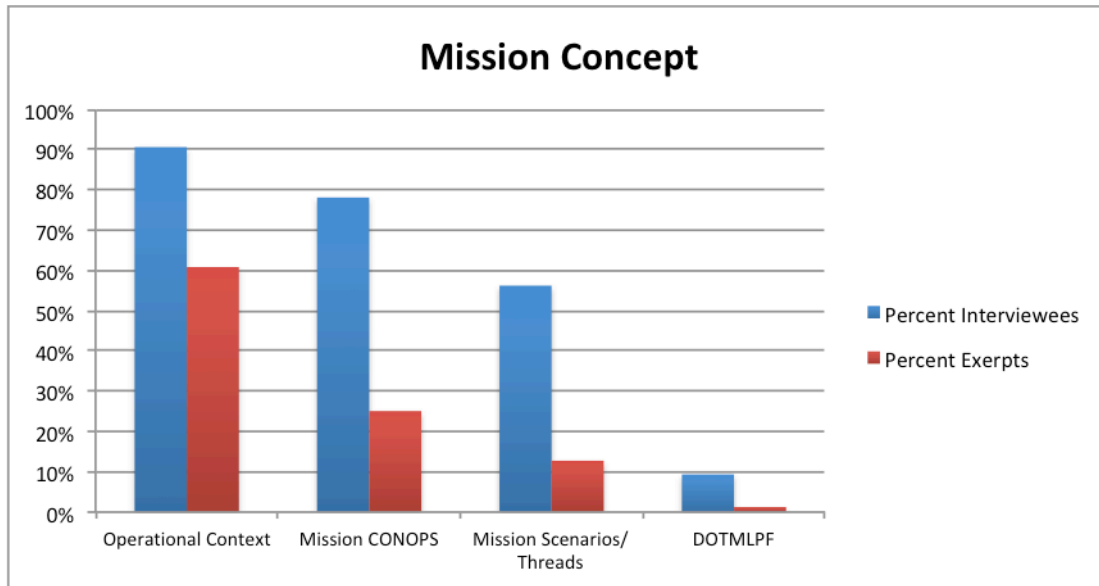
Figure 34. Mission Concept Competencies (N=32 interviewees; 235 excerpts)

The Mission CONOPS is the view of the critical systems required to complete a mission which highlights how these systems will interact at a high-level to produce the desired mission effects. This was cited by over three-quarters of the interviewees (78%), though was not mentioned as frequently as the operational context. Mission Scenarios/Threads define the end-to-end execution of a mission and enable individuals to understand how all the systems of systems work together, and were also cited by the majority (56%) of the interviewees. The final category in this area is DOTMLPF – an acronym that stands for Doctrine, Organization, Trainingl, Materiel, Logistics, Personnel, Facilities. In this context, this competency describes the ability to define a mission not only by the systems involved but also across the non-materiel space, including how it could be used, how it might operate, how it could be supported, etc. Excerpts about the DOTMLPF competency described how critical it is that mission engineers look across the space and do not focus solely on materiel solutions.

E.1.3 SYSTEMS ENGINEERING SKILLS

It should not be surprising, given the strong relationship in the interview data between mission engineering and systems engineering, that systems engineering skills were frequently cited as critical for mission engineers to be successful. There were a total of 380 excerpts regarding systems engineering competencies in the study (covering 45% of the total excerpts on technical competencies). Figure 35 provides an overview of the various systems engineering competencies described in the interviews.
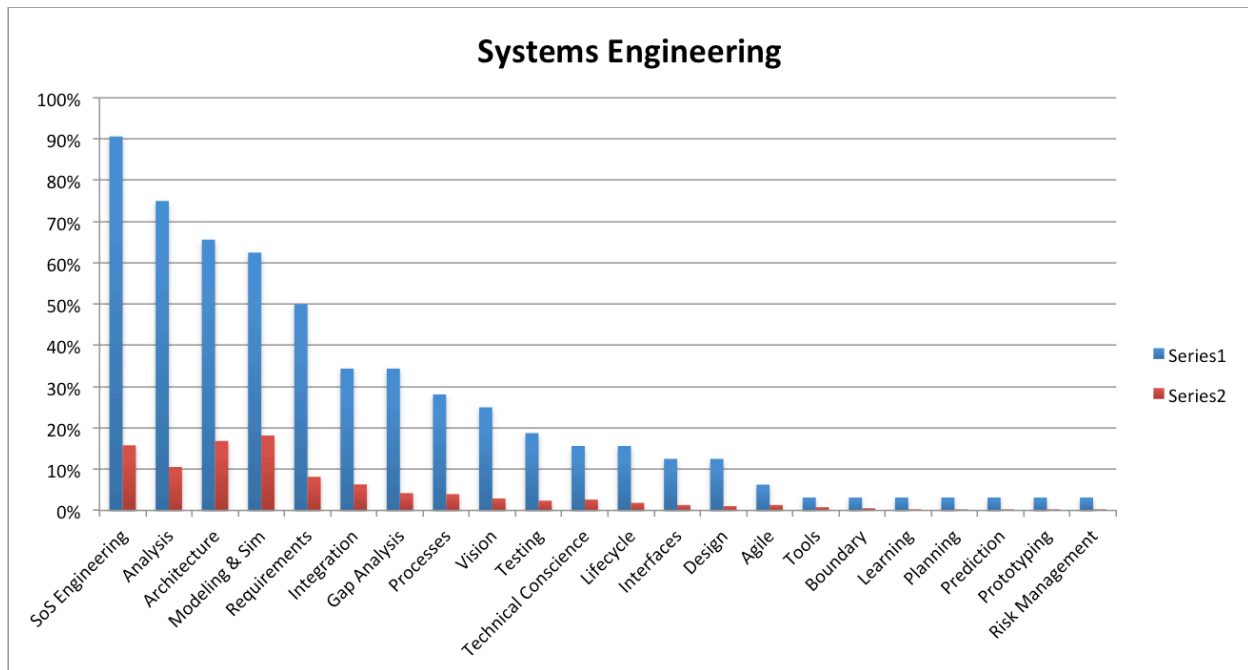
Figure 35. Systems Engineering Competencies (N=32 interviewees; 380 excerpts)

Because there were 22 individual competencies identified, to make cutoff determinations for systems engineering skills, the first metric was the percentage of interviewees who described a specific capability. For instance, while agile methods, critical tools, and prototyping were all described, they were each described by only a single individual in the sample, meaning it is reasonable to leave them out of the ME Competency Framework. This does not mean that these skills are unimportant but that perhaps they are more crucial in certain organizations or for a very specific mission.

Competencies included in the ME Competency Framework related to systems engineering included:

1. SoS Engineering

2. Analysis

3. Architecture

4. Modeling and Simulation

5. Requirements

6. Integration

7. Gap Analysis

SoS engineering was the most commonly-cited skill (91% of interviewees and 16% of excerpts) and emerged in two ways: either individuals specifically cited SoS engineering as a critical skill or individuals cited "systems engineering" as a critical skill, but they had defined "mission"

systems as SoS's and had stated that the SoS perspective was critical. Likewise, Analysis, Architecture, Modeling and Simulation, and Requirements were all heavily cited as important. The cutoff for inclusion in the Systems Engineering area was competencies cited by at least 34% of the interviewees, which incorporated Integration and Gap Analysis.

However, it is important to note that the ME Competency Framework is intended to be tailored and, to that end, it is likely that the Systems Engineering area would be tailored to highlight crucial skills for certain types of systems, operational contexts, etc.

E.2 SYSTEMS MINDSET

The Systems Mindset area is primarily focused on patterns of thinking, perceiving, and approaching a task that are particularly relevant to mission engineers. Of the 32 interviewees, 91% (29 individuals) described the importance of the systems mindset. As part of the methodology, the *Atlas* proficiency model was provided as a read ahead to the interviewees. Interestingly, the concept of "systems mindset" resonated with many of these individuals. In fact, 45% of the excerpts around systems mindset were specifically referencing the *Atlas* model; these made up 45% of the total excerpts.
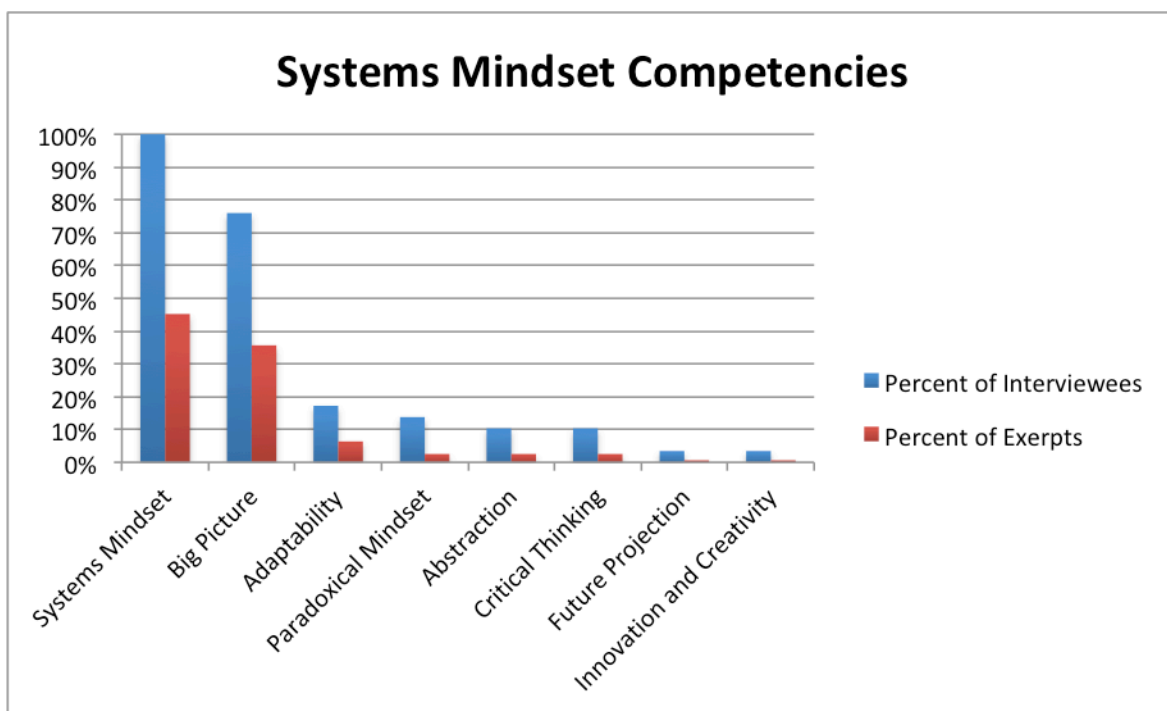

Figure 36. Systems Mindset Competencies (N=29 interviewees; 157 excerpts)

Big picture thinking – which includes the ability to step back and take a broader view of the problem at hand – was cited as important by 76% of the interviewees. The competencies of future projection and innovation and creativity were highlighted by only one interviewee, so

were not incorporated into the competency framework. However, if additional data were collected and added to the dataset, this could change.

Competencies included in the ME Competency Framework related to systems mindset included:

1. Big Picture

2. Adaptablity

3. Paradoxical Mindset

4. Abstraction

5. Critical Thinking

E.3 "Non-Technical" Competencies

These skills, which might also be referred to as "soft skills" are nonetheless critical for the successes of mission engineers. These competencies were grouped into two areas: Interpersonal Skills and Techncial Leadership. In total, 30 individuals (94%) described these skills as critically important for mission engineering. There were a total of 411 excerpts regarding these "non-technical" competencies, which included overlaps in coding between related competencies.

E.3.1 Interpersonal Skills

For interpersonal skills, 30 individuals (94%) provided 199 individual excerpts on the importance of interpersonal skills for mission engineers. Figure 37 provides an overview of the categories in this competency area:

1. Communication

2. Translation

3. Enterprise Context

4. Building & Utilizing a SME Network

5. Coordination

6. Influence, Persuasion, and Negotiation
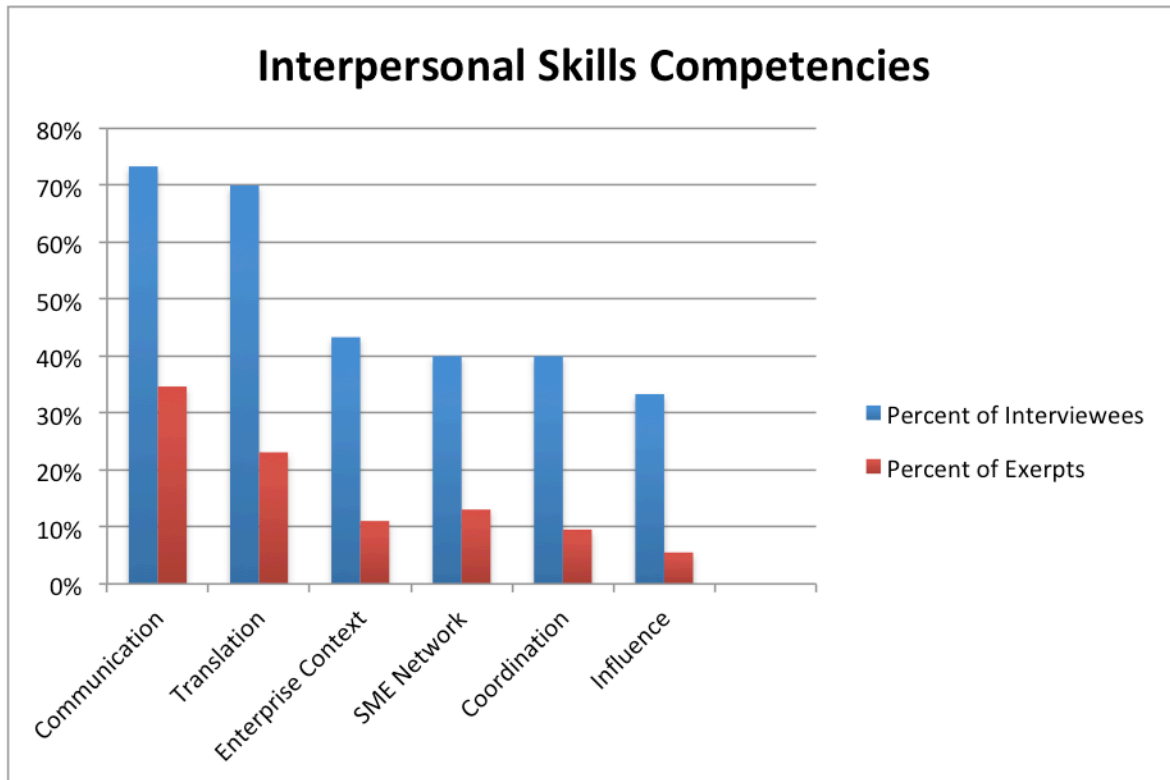
Figure 37. Interpersonal Skills Competencies (N=30 interviewees; 199 excerpts)

The first two categories were described by over two-thirds of the interviewees. In fact, translation is a very specific type of communication, in which the concerns of a given stakeholder are "translated" into the language of another stakeholder. The team initially considred combining these, but the data was divided into these two groups: general communication skills and this specific idea of translation. Because 70% of the interviewees specifically cited translation, it was kept as a separate category, though it is of course closely tied to communication.

E.3.2 TECHNICAL LEADERSHIP

For Technical Leadership, 30 individuals (94%) provided 139 excerpts that described these critical skills. Figure 38 provides an overview of the different competencies identified and how they have been grouped into categories for the ME Competency Framework:

1. Guiding Diverse Stakeholders

2. Team Building

3. Political Savvy

4. Decision Making

5. Workforce Development
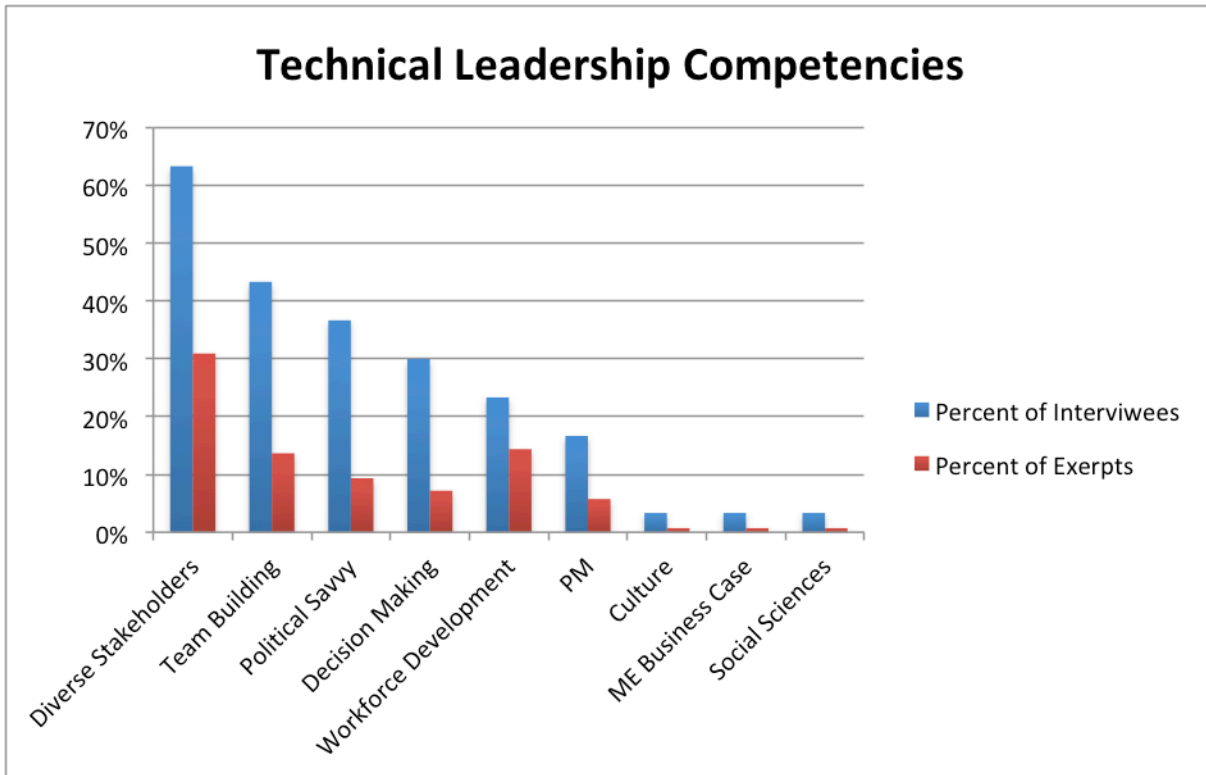
Figure 38. Technical Leadership Competency Categories (N=30 individuals; 139 excerpts)

The guidance of diverse stakeholders emerged as a clear theme in the data, with two-thirds of the interviewees citing this as a critical skill. Team building, political savvy, decision making, and workforce development also emerge. The team considered not including workforce development, as this is required in any discipline, but most interviewees who discussed workforced issues described a situation in which they were not sufficiently staffed to perform ME and were simultaneously trying to perform ME while growing new MEs. As this addresses a critical challenge, it was included by the team. Project management (PM) was cited by 17% of the interviewees who discussed technical leadership, but 60% of these individuals were from the same organization. Therefore, it was determined that this may be critically important in some contexts, but does not rise to the level of individual framework. Likewise, because culture, a providing a business case for ME, and the social sciences were mentioned by few interviewees, they may be important in some contexts but were not included in the ME Competency Framework.

APPENDIX F: EXISTING ACADEMIC PROGRAMS IN MISSION ENGINEERING

Table 14 provides a listing of all programs that have mission engineering related curricula identified by the RT-171 team.

Table 14. Academic Programs with Mission Engineering-Related Courses

University Name	Course Name	Course Description
Air Force Institute of Technology	System of Systems	The System of Systems course provides an overview of how systems engineering process elements are applied to the planning, development and fielding of a system of systems capability. The course assumes basic understanding of systems engineering process elements.
California Institute of Technology	System of Systems	This program is designed to provide participants with a full understanding of the challenges of engineering and integrating system of systems. At the conclusion of this certificate program, participants will understand the application of processes, methods and techniques (and their extensions) to the unique challenges of engineering and integrating system of systems.
Commonwealth Graduate Engineering Program Universities: George Mason University, Old Dominion University, University of Virginia, Virginia Commonwealth University, and Virginia Tech	System of Systems Engineering	Comprehensive treatment of System of Systems Engineering (SoSE), including; fundamental systems principles, concepts, and governing laws; complex and simple systems; underlying paradigms, methodologies and essential methods for SoSE analysis, design, and transformation; complex system transformation; current state of SoSE research and application challenges. Explores the range of technological, human/social, organizational/managerial, policy, and political dimensions of the SoSE problem domain.
Johns Hopkins University	System of Systems Engineering	This course addresses the special engineering problems associated with conceiving, developing, and operating systems composed of groups of complex systems closely linked to function as integral entities. The course will start with the underlying fundamentals of systems' requirements, design, test and evaluation, and deployment, and how they are altered in the multi-system environment. These topics will then be extended to information flow and system interoperability, confederated modeling and simulation, use of commercial off-the-shelf elements, and systems engineering collaboration between different organizations. Advanced principles of information fusion, causality theory with Bayesian networks, and capability dependencies will be explored. Several case studies will be discussed for specific military systems of systems, including missile defense and combatant vehicle design, as well as selected commercial examples.

University Name	Course Name	Course Description
Naval Postgraduate School	System of Systems Design and Development	This course discusses the special problems of managing and engineering system of systems from the LSI perspective. Topics include characteristics of SoS in the LSI management environment, engineering implications of SoS issues, management and engineering methodology of SoS, SoS architecture, analysis of SoS, and tools for engineering and monitoring SoS. Managing the integration of SoS through an LSI requires attention to the meta-systems implications of changes at the systems level. This course discusses the special problems of managing the integration of system of systems from the LSI perspective. Topics from the LSI perspective include the characteristics of the large scale SoS, program management of SoS integration, uses of SoS design and architecture for decision analysis, feasibility analysis and approaches for SoS integration, SoS contract management, and execution for SoS acquisitions.
Purdue University	System of Systems Modeling and Analysis	The goal for this course is to enable students to characterize, abstract, model, simulate, and analyze a special kind of system termed a system-of-systems (SoS). The course will cover a select few topics in detail, but also expose students to interesting areas of further study and highlight the importance of SoS in society. The course presents recent developments in frameworks for formulating system-of-systems problems, lexicon for their articulation, and analysis methodology for their study. Through individual and team projects, students gain experience in formulating problems and applying theory and techniques. Applications for team projects will include transportation, space exploration, energy, defense, and infrastructure, though others are possible in consultation with instructor.
University of Southern California	Systems/System-of-Systems Integration and Communication	Essentials of systems and system-of-systems integration from the perspectives of business, programs, and technology. Process, Legacy, and Systems-of-Systems Integration. Verification and Validation methods. Case studies.

Table 15 provides an overview of the only mission engineering degree program identified by the RT-171 team. This unique graduate certificate is offered by Old Dominion University (ODU) in Mission Engineering and Analysis (ODU, 2017).

Table 15: Courses and Descriptions of ODU's Graduate Certificate in Mission Engineering and Analysis

Course Number	Course Name	Course Description
ENMA640	Integrated Systems Engineering I (prerequisite to ENMA650)	This course examines the role and nature of systems engineering. It is specifically designed to provide the fundamental understanding of systems engineering and complex systems. This course examines a variety of systems engineering topics with emphasis on the: (1) development of the fundamentals of systems engineering, (2) systems engineering life-cycle models and phases, (3) systems design for operational feasibility, and (4) an introduction to planning for systems engineering and management. This course prepares students to assume the role of a systems engineer in planning, directing, conducting, and assessing systems engineering initiatives.
ENMA650	Mission Analysis and Engineering (required)	The course provides an overview of mission engineering and the role of mission engineering and the mission engineer in government acquisitions. The course presents the theoretical foundations that enable a fuller representation of complex problem as well as the required engineering and management approaches needed to deal with the high level of complexity and uncertainty. It applies the theoretical facets to specific engineering problems/cases and explores robust approaches given the conditions of the problem. Developments, on-going research, as well as gaps in knowledge and know-how are discussed. Prerequisites: ENMA 640.
ENMA660	System Architecture (elective)	Students learn the essential aspects of the systems architecture paradigm through development and analysis of multiple architecture frameworks and enterprise engineering. Emphasis is placed on systems modeling and enterprise engineering.
ENMA702	Rational Decision Making (elective)	The goal of this course is to enhance the student's ability to make rational and strategic decisions in complex situations. The course is split in two modules: decision theory and game theory. The decision theory module focuses on how individuals make complex decisions, both from a prescriptive (ideal) and descriptive (actual) perspective. The game theory module focuses on strategic decision-making in situations where individuals must interact with one another.
ENMA715	System Analysis (elective)	The course is designed to provide an understanding of the interdisciplinary aspects of systems development, operation, and support. The course focuses on the application of scientific and engineering efforts to transform an operational need into a defined system configuration through the interactive process of design, test, and evaluation.
ENMA750	System of Systems Engineering (elective)	Comprehensive treatment of System of Systems Engineering (SoSE), including; fundamental systems principles, concepts, and governing laws; complex and simple systems; underlying paradigms, methodologies and essential methods for SoSE analysis, design, and transformation; complex system transformation; current state of SoSE

Course Number	Course Name	Course Description
		research and application challenges. Explores the range of technological, human/social, organizational/managerial, policy, and political dimensions of the SoSE problem domain.
ENMA755	**Human Systems Engineering (elective)**	This course introduces the concepts of Human Systems Engineering, focusing on designing systems that include human components. Human System Integration and Human Factors Engineering are discussed, as well as other human centered design approaches. The role of human data in system of systems design is explored, and methods to capture and represent human data, including architecture frameworks, are presented. Modeling and analysis of human centered systems is done through hands-on projects.
ENMA605	**Capstone Course (required)**	In this course you will apply your knowledge of all four courses through project-based learning. Most students choose a project whose results will benefit their own organization.

APPENDIX H: ISO/IEC/IEEE 15288 2015 SYSTEMS AND SOFTWARE ENGINEERING – SYSTEM LIFE CYCLE PROCESSES

The following guidelines address the application of SE to SoS, based on the DoD Guide to SE for SoS (2008) and the International Organization for Standards/ International Electrotechnical Commission/ Institute of Electrical and Electronics Engineers (ISO/IEC/IEEE) 15288:

ISO/IEC/IEEE 15288: 2015 establishes a common framework of process descriptions for describing the life cycle of systems created by humans. It defines a set of processes and associated terminology from an engineering viewpoint. These processes can be applied at any level in the hierarchy of a system's structure. Selected sets of these processes can be applied throughout the life cycle for managing and performing the stages of a system's life cycle. This is accomplished through the involvement of all stakeholders, with the ultimate goal of achieving customer satisfaction.

ISO/IEC/IEEE 15288: 2015 also provides processes that support the definition, control and improvement of the system life cycle processes used within an organization or a project. Organizations and projects can use these processes when acquiring and supplying systems.

ISO/IEC/IEEE 15288: 2015 concerns those systems that are man-made and may be configured with one or more of the following system elements: hardware, software, data, humans, processes (e.g., processes for providing service to users), procedures (e.g., operator instructions), facilities, materials and naturally occurring entities.